ASSESSMENT OF DEGRADATION OF SHALEY LIMESTONE RIPRAP

by

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A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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Abstract

Limestone riprap, at a site consisting of a series of dykes in Northern Canada, is degrading and much of it will require replacement in the near future. The challenge is determining the capacity of this riprap to protect against the environmental demands, and to manage cost effective riprap replacement programs.

During field studies in 2001 and 2002, an average of 14 "large" riprap (larger than 0.20 m on two sides) per metre were measured at selected sites, with an average nominal diameter of 0.33 metres. Compared to similar data collected in 1998, the number of "large" rocks increased by as much as 2 to 3 rocks per square metre and the size of these rocks decreased by as much as 0.1 metres. One possible theory is that many "large" rocks are breaking into two or more "large" rocks.

Laboratory tests were conducted on limestone riprap samples from the site being studied. Limestone samples had only trace losses during wetting-drying tests. Freezing-thawing tests were extended past the number of ASTM recommended cycles to simulate losses reported in the field, yet more than half the limestone samples had losses of less than 1%. The absorption of limestone did not correlate to its durability in freezing-thawing. A test called the Iowa Pore Index Test, which takes less than 30 minutes to perform, was found to have good correlation with freezing-thawing tests. All samples which had an Iowa pore index greater than 27 also had freezing-thawing losses greater than 4%, while those with 27 or less had freezing-thawing losses less than 1.5%.

Fetches, at the site being studied, vary from 53 metres to 19.3 km, while wave heights for a 1 in 100 year wind event, vary from 0.7 to 3.0 metres. Wave heights on dyke faces were found to correlate poorly to number and size of riprap. Studies reported in this thesis suggest that the current capacity of some of the riprap provides insufficient protection against storm wave damage. Further studies are required to develop relationships between capacity and demand of limestone riprap, to create cost effective riprap management programs.

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α	angle of dyke slope from horizontal (Chapter 2)
γ_r	unit weight of Limestone rock
θ	angle of dyke slope from horizontal (Chapter 6)
a	angle from the current radial to central radial
A	mass of oven dry specimen in air (Chapter 5)
A_1, A_2	absorption of specimen (Chapter 5)
B	mass of saturated surface dried specimen in air (Chapter 5)
C	mass of saturated specimen in water (Chapter 5)
D_{50}	average diameter of the median rock found by weight
H_s	design or significant wave height
K_D	stability coefficient, varies with size and shape of rock and type of waves
P_1, P_2	percent of specimen mass from the total of both specimens (Chapter 5)
G_1, G_2	bulk specific gravity of specimen (Chapter 5)
S_r	specific gravity of rock
T_{min}	minimum thickness of the riprap layer
W_{50}	minimum weight of the median sized rock
X_k	fetch length of 1 of 15 radials

Chapter 1: Introduction

Riprap along the dykes at the site being studied in this research project has been degrading since it was initially installed at a rate faster than expected. Riprap is rock material, of a designated average size, that is placed on the reservoir dykes to protect against wave action and erosion. The purpose of this research is to determine the mechanisms involved in the degradation of the limestone riprap, the influence of these mechanisms along the length of the dyke system, and find the areas most affected. The owner has been proactive in undertaking remedial work and requested this study in order to be proactive in their management of the site.

1.1. Background

The site being studied in this research project is located in Northern Canada. The owner requested that the site studied is not identified, so information revealing the site location is not included.

The shoreline protection along the dykes at the site studied in this research project consists of limestone riprap, used to minimize erosion of the dykes by wind-generated waves. The dykes are up to 30 m high and 28 km long. Environmental factors such as wind fetch, wave height, and bathymetry vary considerably along this length. As the riprap protects the dykes against erosion, the rock itself is slowly being degraded by environmental factors.

The riprap was originally obtained from quarries at or near site, which produced argillaceous limestone, meaning it contains silt or clay partings or seams within the limestone. This riprap was first placed during construction in the early 1960's, with an average design diameter of 500 mm. Better quality granite riprap is only available from distant quarries at considerably higher cost. At the time of construction, it was believed the locally available limestone would provide adequate protection at a reasonable cost, despite the fact that it would require regular replacement maintenance. Recent policies of the owner have been to replace riprap when local inadequacies were observed. It is now believed that the local limestone is degrading at a rate that makes it unsuitable for future use and that large sections of the dykes will require new riprap.

1.2. Problem

The riprap at the site studied is breaking down at a faster rate than anticipated and it has reached a point where major work is required over the next few years to upgrade the protection of the dykes. Without replacement, a 'failure' of the riprap may occur, meaning it may not adequately protect the dykes and some sections may be at risk of erosion damage caused by wind-generated waves. It is anticipated that replacement of the riprap will be done on a sequential basis over a number of construction seasons. During this process, the reliability of the dyke structures must be maintained. The process must target the areas with the highest probability of failure first and then strategically replace the riprap in sequence.

As a rock type, limestone is not generally considered suitable for erosion control due to its poor performance in the tests such as freezing-thawing and wetting-drying that are generally used to assess durability. These tests are designed to approximate conditions in the field and assess the rock's ability to withstand these conditions. The locally derived limestone riprap is not only problematic because it is limestone, but also because of its argillaceous and bedded nature, which may further weaken the rock.

Due to the design of the dyke system, riprap along the dykes is exposed to different local environments, as a result of orientation to prevailing winds, 'fetch' distance across the reservoir surface, wave energies, dyke height, and slope. Each of these factors has different effects on the local degradation of the riprap and likelihood of failure of that riprap. Some zones, with good quality limestone and short fetches are less likely to experience a 'failure' of the riprap. Others, with poor quality limestone and longer fetches in the direction of the prevailing wind, are more likely to experience 'failure' of the riprap.

For planning future riprap replacement programs an analysis is required of the mechanisms of failure of the riprap and methods of assessing the areas most like to reach 'failure'. This analysis will allow the owner to respond in a planned way to undertake the needed replacement of riprap. If deterioration continues unchecked, there is danger of wave action attacking the crest of the dyke, leading to overtopping, and erosion in portions of the dyke system (USBR 1977).

1.3. Hypothesis

> The protective *capacity* of the riprap is directly related to the size and amount of riprap protecting the dykes and the ability of that riprap to withstand environmental factors, such as wave action and damage by freezing-thawing and wetting-drying cycles.

The *capacity* of the riprap to protect the dykes from wave action decreases as the limestone riprap deteriorates and the average size of the blocks decreases. The *demand* on the riprap varies, depending on the local dyke slope, height, bathymetry, wind velocity, orientation to wind, 'fetch' distance across the reservoir surface, and wave energies. This project examines the relationship between the factors affecting *capacity* and *demand,* and determines the areas where failure is most likely to occur.

Using statistical analysis to relate the material properties of the riprap, mechanisms of physical deterioration, environmental factors, and position along the dykes, this project shows the evolving pattern of riprap degradation. This analysis will allow the owner to plan the timing of riprap replacement based on how the riprap has deteriorated and the conditions that may lead to further deterioration in each area.

1.4. General Scope

The objective of the project is to develop empirical relationships between:

- physical properties of the limestone riprap,
- ability of the limestone to pass standardized durability tests,
- current dimensions of the riprap,
- time since placement,
- environmental factors (including information about fetch, prevailing wind direction and wave energies), and
- location on the dyke.

The project involves:

- a study of the capacity of limestone to withstand the processes of degradation,
- an evaluation of the performance, size and amount of limestone riprap at the site being studied in this research project since first construction and specifically between a series of successive field studies,
- an assessment of the demand on the riprap based on the environmental conditions as a function of position in the dykes,

- an analysis that will lead to effective management of construction programs for systematically replacing inadequate riprap at this site, and potentially at other similar sites.

This analysis includes distribution functions for parameters such as aggregate characterization, degradation rate, dyke height, orientation, fetch distance, wind intensity, wind direction and position. This research quantifies these relationships with respect to position along the dykes. Because of the highly variable nature of the parameters, the dykes are divided into area of similar environmental conditions.

In order to fulfil each of the points listed above, a review of the literature relating to each topic is required to identify and understand the factors involved in this research. This review also shows this research is necessary to provide a thorough analysis of the riprap problems at this site, and to determine the mechanisms involved in riprap degradation, the influence of these mechanisms, and the areas most affected.

Chapter 2: Literature Review

A review of the literature in the subjects of riprap and shoreline protection will provide an understanding of the nature and processes of riprap disintegration and shoreline protection. This section introduces these concepts and applies them to the specific conditions that are present at the dykes at the site being studied. This review of the literature identifies the need for research on limestone riprap and is the starting point for creating relationships between the capacity of limestone riprap in terms of its durability, and the demand in terms of wave action, wetting-drying and freezing-thawing at the site being examined.

2.1. Introduction

Slope protection is required on all earth dykes to protect against erosion of filter and core materials. Without protection, this material is vulnerable to wave attack. Material will be removed every time a wave breaks on the dyke face and significant erosion will occur during every substantial wave event. Eventually there must be concern that erosion will progress to a point where the dyke will not be able to support the upstream reservoir. To prevent this, upstream slopes of earth-filled dams and dykes are usually protected by one of four basic forms of protection: dumped rock riprap, hand-placed riprap, articulated concrete paving stones, or continuous reinforced concrete pavement. Each is designed specifically to dissipate wave energy, preventing removal of filter and core materials.

At the site being studied for this research project, dumped rock riprap from local quarries was used to protect the dyke slopes. Quarry-sourced dumped rock riprap is the most common form of earth dyke protection used. Since it is so widely used, there are plenty of examples of successful applications and design procedures have become standardized (McDonald 1988). The local quarries near the site being studied in this project produced limestone, which in some cases was shaley or argillaceous and bedded. The concern being studied is whether the limestone riprap can withstand the environmental conditions placed on it over an acceptable time span.

2.2. Erosion and Wave Energy

2.2.1 Erosion Processes

Erosion of the riprap and dyke face is due to environmental processes that act on the dyke (Thomas 1976, USBR 1977, Golze 1977, Fookes and Poole 1981). These environmental processes can take a number of forms, including:

- abrasion by wave action,
- disintegration due to wetting and drying,
- disintegration due to freezing and thawing,
- abrasion by wind blown materials,
- abrasion by ice and other floating debris,
- rain and snow-melt runoff, and

- burrowing animals.

All earth dyke designs must incorporate measures to protect the exposed faces of the dykes against these environmental processes.

The most common form of slope protection is riprap, that is pieces of rock placed in such a way that they protect the dyke face from wave action (Thomas 1976, USBR 1977, Golze 1977, McDonald 1988). They do this by dissipating the energy of the waves. The rock is designed and graded to protect the dyke from wave action, based on estimates of fetch, wind speed and depth. It is put in place along the dyke face by dumping or by placing as individual pieces.

Riprap is subjected to erosion and disintegration. Wave energy will displace or slowly destroy individual rocks. Wave energy can also produce "spoon-holes" (which are localized holes in the riprap protection), washout of bedding material from between the riprap, and beaching at the wave breaking level (Lefebvre et al 1992, Rohan et al 1994). Meanwhile, wave run-up wets the rock along the bank, subjecting it to wetting and drying cycles, and making it more vulnerable to destructive freezing and thawing cycles. Finally, if the dyke face is steep enough, any holes in the riprap can initiate sliding of the riprap down from the crest, which can further damage rock at water level.

According to McDonald 1988, "The greatest uncertainty in design arises from the difficulty in estimating the environmental design conditions." This research considers only the environmental conditions of wetting and drying, freezing and thawing, and the wave energies that need to be dissipated by the riprap at a study site in Northern Canada.

2.2.2 Wave Height

Higher wave heights impart more wave energy to the dykes and wet the rocks further up the banks. Wave height is variable from location to location along the dykes, depending on the conditions that create the waves. The conditions usually considered in calculating wave height are the wind speed and fetch.

Wind speeds used for calculating wave heights are determined using local wind speed data grouped by compass direction. These data are used to determine the average wind speed for events reoccurring with certain return periods, for example 50 year or 100 year return periods. These data are often displayed as a wind rosette, showing the wind speed and return period for each compass direction.

The wind speed used for design of waves in areas with significant exposure to wave action is generally the wind speed during events that occur once in 100 years (Acres 1988). Where the exposure is less, the design wind speed used may be the 1 in 50 year event.

Wind speeds are usually taken at land based locations. However a large water mass provides less friction and the wind speed over water tends to be higher than over land. Wind speeds taken over land are increased by a factor based on the fetch to approximate the actual wind speed over water. This factor ranges from 1.08 for a fetch as short as 1 km, to a maximum of 1.31 for fetches 10 km or longer (Acres 1988).

The fetch is generally considered as the distance across a body of water, which allows for the build-up of wave height. In basic terms, the longer the fetch distances the greater the wave heights. The worst case fetch length is determined as the distance from the dyke face intersecting the shoreline either perpendicular to the dyke face, or in the direction of the critical wind incidence (Peters and Towle 1979, SEBJ 1997).

For design, an effective fetch length is often used. It is calculated using an averaging technique (Saville et al. 1962, Peters and Towle 1979, Acres 1988). This average is found by drawing 15 radials from the dyke face to intersect with the shoreline across the basin. The central radial is perpendicular to the dyke face and the other radials are at intervals of 6°. This effective fetch is found as according to the formula:

$$\text{Effective Fetch} = \frac{\sum_{k=1}^{15}\left(X_k \cos^2 a_k\right)}{\sum_{k=1}^{15}\cos^2 a_k} \qquad [2.1]$$

Where

X_k is the fetch length of 1 of 15 radials, and

a_k is the angle from the current radial to central radial.

The United States Army Corps of Engineers (1984) recommend a similar procedure, but they use 9 radials and an angle of 3° between. SEBJ (1997) also uses a similar procedure, measuring the fetch at each degree for 180° (90° on each side of the central radial).

Once the wind speed and fetch distances are found, there are a number of different methods of determining wave height. Depending on the amount of safety desired, the wave height chosen can be the significant wave height or the average of the highest 10% of all wave heights (H_{10}). The significant wave height corresponds to the average of the highest one-third of a wave group for a specified fetch and wind speed. The methods of determining these wave heights are complex and beyond the scope of this thesis. To simplify, the wave heights are often summarised in charts or tables (USBR 1977, U.S. Army Corps of Engineers 1984, Acres 1988). This research project will use the methods and tables discussed in Acres 1988.

It is widely accepted that flatter slopes generally have less erosion than steeper slopes. This is reflected in values chosen for the stability coefficient using Hudson's equation, which will be introduced in section 2.3, (Acres 1988, McDonald 1988). The stability coefficient values translate into larger rock being required for steeper slopes and smaller rock for flatter slopes (Sorensen 1997). (Flatter dyke slopes mean that more wave energy is expended in water rushing up the slope.) Dumped riprap provides a rough surface that reduces wave run-up energy more than smoother faces, such as placed rock or concrete (USBR 1977). This dissipation of energy reduces the amount of erosion to the filter and core material below the riprap. There are concerns that with sufficient movement of rocks, the upper layers of riprap may also slip down (Sherard et al 1963, USBR 1977).

Rohan et al (1994) found that for steep dykes, any holes in the riprap coverage within the dyke could lead to riprap sliding from the crest down into the hole. To some extent, this provides a short lived "self-repair" of the damaged dyke section, but once the "new" rock is broken down, the dyke is exposed all the way up to the crest. Fines or small material also play a part, and increase the sliding action. In theory, wave energy should be more able move pieces of riprap on a steeper slope (Sherard et al 1963).

2.2.3 Dissipation of Wave Energy

The force imparted by a wave depends on the height of the wave, whether it breaks, the roughness of the material it washes over, and the slope of the dyke face (Sherard et al 1963, United States Army Corps of Engineers 1984). Wave energy is dissipated when wave motion becomes turbulent as it rushes up the slope and around the rocks. This turbulent action may do two things: (1) erode the filter layer between the rocks, which eventually can lead to down-slope movement of the riprap, or (2) lift the riprap pieces and remove rock from the slope face, if there is enough energy. During a storm event when the riprap is moved bodily or rolled down-slope, a beach is created in the area where the waves are beating.

Angular quarried rocks in which the angular pieces interlock and defend against the wave energy perform better than rounded rock, which can be displaced more easily (USBR 1977, Sorensen 1997). Where rounder rock is used, the bank needs to be flatter to help prevent movement and a thicker layer is recommended as extra protection. Otherwise, larger sized riprap must be used. The riprap at the site studied in this research consists entirely of quarried rock.

The forces exerted by a wave on an individual rock have been theoretically calculated (USBR 1977) and the size of rock required to withstand that wave can be determined. These calculations have been found to correspond well with results from studies on dams (USBR 1977). They form the basis of the design methods currently used for riprap.

2.2.4 Ice sheets

Physical properties of ice sheets are not consistent, but vary considerably from location to location even within one lake, depending on the grain type and crystal orientation of the local ice (McDonald 1988). The properties also vary with temperature and strain rate. Ice is generally ductile at low strain rates while elastic and brittle at high strain rates. As a result, the overall effects on a structure are exceptionally difficult to calculate accurately and local effects can vary considerably. The main forms of possible riprap damage due to ice loads are abrasion, plucking and movement due to ice ride-up.

Vertical uplift forces occur when an ice sheet freezes to a rock and then "plucks" it out of its location when the water level in the reservoir increases. Since most rock typically weighs 2.9 times as much as ice, this is usually limited to small sized rocks (McDonald 1988, Acres 1988). Acres (1988) reported this type of damage has been noticed along dykes in northern Canada. The report specifically refers to an incident where riprap as large as $D_{100} = 1.0$ m ($D_{50} = 0.6$ m) was damaged by plucking during an increase in the reservoir level. The authors speculate that the ice sheet may have been as thick as 0.7 m. This type of damage can be minimised by designing the riprap D_{50} size so it is greater than the expected thickness of the ice sheet (Acres 1988).

Ice sheets can be pushed up or down dyke faces by wind action, changes in temperature or changes in reservoir level (McDonald 1988, Acres 1988). These movements of the ice sheet can push riprap out of place. The Acres report (1988) discusses several examples of this problem. Movements may be more significant on steeper slopes, and again, the recommendation is to design riprap D_{50} size so it is greater than the ice sheet thickness.

In most cases, the D_{50} designed from Hudson's formula is considered large enough to withstand ice forces (SEBJ 1997). This research project does not consider effects of ice sheets.

2.3. Riprap Design

Hudson (1949) conducted experiments with rubble mound breakwaters and developed a formula for determining the weight of rock required to protect against damage.

$$W_{50} = \frac{\gamma_r H^3}{K_D (S_r - 1)^3 \cot \alpha} \qquad [2.2]$$

Where:

W_{50} = minimum weight of the median sized rock,

γ_r = unit weight of the rock,

H = design or significant wave height,

K_D = stability coefficient, varies with size and shape of rock and type of waves,

S_r = specific gravity of rock, and

α = angle of dyke slope from horizontal.

This formula is the recommended standard for current practice (Peters and Towle 1979, United States Army Corps of Engineers 1984, Acres 1988, McDonald 1988, Sorensen 1997, SEBJ 1997).

Typical values used for the stability coefficient are 2.2 for graded angular riprap on large dykes with large fetches and 3.2 for angular riprap on small dykes with flatter slopes and smaller waves (Acres 1988). Stability coefficients can go as low as 1.1 for smooth round rock on large dykes with long fetches or as high as 4.2 for rough angular rock on small dykes with no breaking waves (Acres 1988, McDonald 1988, United States Army Corps of Engineers 1984).

Minimum weights from equation [2.2] can be transformed into dimensions using the formula:

$$D_{50} = \left[\frac{(W_{50})}{\gamma_r}\right]^{\frac{1}{3}} \qquad [2.3]$$

Where:

D_{50} = average diameter of the median rock found by weight,

W_{50} = weight of the median sized rock, and

γ_r = unit weight of the rock.

The riprap should be graded so voids between the larger rocks are filled, preventing erosion of the filter material and core from between the larger rocks. Most agencies, for example, Acres (1988), recommend a gradation:

$$\text{Maximum rock size} = 4\,W_{50} \qquad [2.4]$$

$$\text{Minimum rock size} = \frac{W_{50}}{8} \qquad [2.5]$$

The riprap layer must be thick enough to avoid large cavities between the largest rocks and to protect smaller rocks within the system from excessive movement. The most common recommended thickness is:

$$T_{min} = 2\,D_{50} \qquad [2.6]$$

Where:

T_{min} = minimum thickness of the riprap layer, and

D_{50} = average diameter of the median rock found by weight. (Acres 1988)

The United States Army Corps of Engineers (1984) uses a similar method, which incorporates a safety factor, based on experimental observation. In cases where only riprap of a marginal durability is available, the use of thicker layers or oversized riprap and replacement programs are considered acceptable to compensate for rock breakdown (Acres 1988, Sherard et al 1963). The extra cost of construction with low quality rock can be compared with extra transportation costs to obtain higher quality rock.

Dumped riprap performs better than "hand-placed" riprap and fails significantly fewer times (Sherard et al 1963). Movement of a few pieces of dumped riprap usually results in very little change in the overall integrity of the slope protection, while movement of a few pieces of placed riprap can mean exposure of underlying dyke layers. Failures at dams with dumped riprap are generally due to improper size of the riprap, while hand-placed riprap failed due to poor construction (USBR 1977). Dumped riprap is also credited with having significantly less maintenance requirements, as it is generally placed in a thicker layer (USBR 1977).

Dumped riprap must be placed on a properly graded filter to prevent fines from the earthen dyke from being washed out through the voids between the rocks (USBR 1977, Acres 1988, United States Army Corps of Engineers 1984). This bedding layer is often half the thickness of the riprap layer and is sized approximately by the formula:

$$\frac{D_{15}(\text{riprap})}{D_{85}(\text{bedding})} \leq 5.0 \qquad [2.7]$$

2.4. Riprap Physical Properties and Durability

To confirm any particular rock is appropriate to be used for riprap, there are a number of physical properties and durability tests recommended. These include specific gravity, absorption, sulphate soundness, abrasion resistance, freezing-thawing durability, and wetting-drying durability. This research focuses on properties relating to wetting of the rock, specifically, wetting-drying, freezing-thawing, and absorption. Acres (1988) recommends the following as guidelines for acceptable rock quality for northern dams:

• Specific Gravity (ASTM C127, CSA A23.2-12A)	≥ 2.6
• Absorption (ASTM C127, CSA A23.2-12A)	≤ 2.0%
• Freeze-thaw (CRD C144)	≤ 1% loss

Sedimentary rocks such as limestone are often considered unsuitable for riprap due to their susceptibility to freezing-thawing damage (Fookes 1981, Acres 1988, SEBJ 1997). This is thought to be due to the porous nature of these rocks, and specifically the pressures caused by water and ice during freezing. In some cases, limestone has been found to be durable enough to be used as riprap (USBR 1977), although this report singles out limestone with clay or shale seams as poor quality for riprap.

As temperature decreases, the growth of ice crystal extends into pores and an energy gradient is produced between unfrozen water and ice. The smaller the pores, the less stable is the formation of ice crystals and colder temperatures are required for ice crystals to form. Formation of ice crystals creates pressures within the pore system and failure or cracking of the rock fabric occurs when the tensile strength of the rock is exceeded. Higher moisture levels within the pores lead to greater pressures (Litvan 1981, Hermanson 1987, Stark 1989).

The standard ASTM freezing-thawing test is considered one of the best tests for determining rock durability, but it has drawbacks that restrict its usefulness (McDonald 1988). One, the test specimen is cut from a larger rock sample. This specimen may not have any of the larger flaws of the original rock and if it were to break during cutting, that specimen would be discarded. This means the specimen may be inherently of better quality than the original rock sample. Two, the test takes a significant period of time, which means it cannot be used in the field to control the quality of the rock selected for riprap (McDonald 1988)

Compared with limestone riprap, considerably more work has been conducted on the effects of freezing and thawing cycles on concrete and concrete aggregates. One test developed specifically for aggregate durability is the Iowa Pore Index Test. It has been found to correlate well to ASTM freezing and thawing tests for aggregates in concrete (Marks and Dubberke 1982, Koubaa and Snyder 1996).

The Iowa Department of Transportation identified that "D-cracking" in concrete was related to freezing-thawing damage and that this damage is somehow related to the size and number of pores in the aggregate material. They designed and conducted a series of experiments, injecting water into pores at various pressures to determine if they could find relationships between the source aggregate and concrete that was known to be susceptible to D-cracking. They found a relationship, which depended on the applied pressure and length of time. This relationship formed the Iowa Pore Index (Marks and Dubberke 1982, IDOT 1980). (See Appendix A for further information.) This test has been used with considerable success in this research (see Chapter 5).

At the current time, the Los Angeles Abrasion Test is the only test of abrasion durability. McDonald (1988) stated "a correlation between the test results and ice abrasion resistance has not been developed." He also mentions that the State of California removed this test from their requirements as they decided it "discriminated unfairly against igneous-intrusive and sedimentary rocks." No abrasion tests were done in this research project.

2.5. Riprap Failure

Riprap "failure" refers to a failure of the riprap layer, where the rock was displaced or degraded and the dykes were no longer protected (U.S. Corps of Engineers 1949, Sherard et al 1963, USBR 1977). The U.S. Corps of Engineers have conducted studies and found that dumped riprap failed in 5% of cases (U.S. Corps of Engineers 1949, USBR 1977, Sherard et al 1963). Meanwhile a study of PFRA dams in Canada (Peters and Towle 1979) found that 5% of their dams were in poor condition or breached as a result of inferior riprap coverage. These dams did not have uniform coverage of riprap and the bedding was exposed locally, allowing erosion. Failure of the riprap rarely leads to a failure of a dam, but if it is left unchecked, erosion will eventually cause a breach in the core.

In most cases, riprap failure is due to inadequate design and an average rock size that is insufficient for the encountered wave action (USBR 1977, Sherard et al 1963). A common design mistake is to use only the fetch taken in a perpendicular line from the dyke face, rather than using the average of a series of radial fetches (Peters and Towle 1979). This latter approach is recommended in many design methods, as has been discussed earlier.

2.6. Summary of Literature and Justification for Project

Based on the review of the literature, the capacity of limestone rock used as riprap has not been thoroughly tested. It is widely accepted that the capacity of riprap is related to its ability to withstand environmental factors. On this basis limestone is often considered unacceptable. Probably for this reason, the literature contains very few studies of limestone riprap and how its physical properties and durability perform in the field. Yet there are times, as in the dykes considered in this project, where thicker blankets of larger limestone riprap could be installed more cheaply than thinner blankets of igneous rock from large distances (approximately 100 km). This was true even taking into account the shorter working life and higher maintenance costs of limestone riprap. There is a need for further study of limestone properties, durability and its ability to withstand wave action, damage by freezing-thawing and wetting-drying cycles both in the laboratory and in field studies.

Chapter 3: Description of Project

Over a number of years, anecdotal evidence at the site being studied in this research project indicated deterioration of the locally obtained limestone riprap. A number of replacement programs were carried out to repair the deterioration, again using the local limestone. Following these replacement programs, a concern emerged that the riprap deterioration was occurring at a rate greater than acceptable. A decision was made by the owners to study the problem. The first study was a field investigation in 1998. In 2001, further study was commissioned in the form of this research.

This project was intended to:

- measure the size of riprap in 2001 and 2002,
- compare size and number of riprap from data collected in field studies conducted in 1998, 2001, and 2002,
- determine if the riprap is disintegrating and where the disintegration is worst,
- determine if there is an association between amount of riprap (size or number) and wave action on the dykes,
- determine which mechanisms are most affecting the disintegration of the riprap, and
- present these data so they are useful for future riprap management programs that guide systematic replacement of riprap.

In undertaking these steps, this project evaluates the capacity of the riprap and assesses whether the riprap has the ability to withstand the demand in the form of the environmental conditions placed on it.

3.1. Site Description

As previously mentioned, the site is quite large (28 km long) with a varied shoreline. The site was originally a winding river valley through a rolling hilly topography. The valley and some of the surrounding area were flooded when the dykes were completed. The dykes were built to fill in the gaps between hills and outlet structures, and to contain the reservoir within fixed boundaries. As a result, the dykes face various directions and the fetches change significantly from location to location.

The dykes are numbered and surveyed based on their position relative to the generating station, starting at 0+00 and increasing away from the centre of the generating station along each of the North and South dykes. The main dykes consist of dykes 1 through 4, South of the generating station, and dykes 1 and 2, North of the generating station. There are a series of small dykes within the bush on the natural hills that are not considered in this study.

Due to topography, the reservoir is deeper towards the centre portion of the dykes and generally not as deep at the ends furthest from the centre. In some areas, natural hills formed islands and peninsulas. Looking along the dyke face, individual reaches may look relatively similar from one end to the other, but the wind and wave effects may be considerably different.

3.2. Organization of Project

The field studies consisted of measuring all "large" rocks within a series of 3 metre x 3 metre grids located across the dyke system. The method is described fully in Chapter 4. An unpublished consultant's report, about a 1998 field study at the site being studied, was made available for this research. This study selected grids at either 100, 200 or 300 metre intervals, apparently depending on the local conditions, such as changes in reaches and dyke direction. It is understood that the specific sites were selected to capture the variations in the changing local wave conditions. In areas where the dyke appears to be protected from wave action, no grids were selected, likely because little or no deterioration was expected in these areas.

In order to utilize the 1998 data, the 2001 field study was organized using the same procedures. These are detailed in Chapter 4. This was beneficial to the study, since the data could then be compared directly over the period of 1998 to 2002. In some cases, the 1998 grids were still visible.

During the field study in 2002, photographs were taken from a boat to get a different view of the dyke system. It was anticipated that evidence of beaching might be visible from a boat and that any systematic evidence of erosion might be more obvious from a boat. The results of this photographic study are presented in Chapter 4.

Although, anecdotal evidence indicates that local ice sheets are potentially causing damage to the riprap, this subject was outside of the scope of the project. The owner reported that the ice sheets are apparently highly variable and shift significantly depending on wind direction. As mentioned in the literature review, the ice sheets are limited in what they can "pluck" from the dyke by the depth of the sheet. The ice sheet depth varies from site to site and year to year. A study of these effects would have required resources outside the scope of this project.

During the 2001 and 2002 field studies, individual rocks were selected for further testing. A small number were weighed and measured during the 2001 field study to determine a relationship between the volume based on outside dimensions and the mass, as discussed in Chapter 4. While analysing these data, it was realized that due to procedural constraints, the rocks selected were significantly smaller than the average rock size and did not accurately represent the size range of riprap on the dyke system. As a result, larger riprap pieces were selected during the 2002 field study. These too were restricted in size due to procedural constraints, but this time the rock sizes were restricted to the largest rocks available. After each of the field studies a number of rocks were shipped to the owner's laboratory for testing.

The processes considered to be chiefly responsible for the degradation of the riprap were wetting-drying and freezing-thawing. The Wetting-Drying and Freezing-Thawing tests were conducted according to ASTM standards, as described in Chapter 5 and generally, less deterioration than expected was found. To encourage more deterioration, the Freezing-Thawing test was extended to 80 days with the specimens covered with cheesecloth to ensure even wetting.

The Iowa Pore Index Test was suggested as an alternative to the Freezing-Thawing test. It can be completed within one half-hour and the specimens can be produced from left over cuttings during preparation for other tests. This test was conducted and the results compared to the Freezing-Thawing results.

Analysis of the data was completed as information was collected. As indicated above, more information, field studies and testing were requested to fill in gaps as required. For example, the owner of the site supplied information such as wind data and maps to determine wave heights. Analysis and discussion of the data are presented in Chapters 6 and 7.

3.3. Summary and Hypothesis

Chapter 1 stated the following hypothesis that would form the basis of this project. "The protective *capacity* of the riprap is directly related to the size and amount of riprap protecting the dykes and the ability of that riprap to withstand environmental factors, such as wave action and damage by freezing-thawing and wetting-drying cycles." The data collected in the field studies and laboratory studies allow for the development of empirical relationships between physical properties of the limestone riprap, the ability of the limestone to pass standardized durability tests, the current dimensions of the riprap and the time since placement. Information was collected from the owner on environmental factors (including information about fetch, prevailing wind direction and wave energies) and their location in the dyke. Taken together, these two sets of data can be used to develop relationships between riprap capacity and demand placed on the dyke system. These relationships provide the background necessary to evaluate the validity of the hypothesis.

Chapter 4: Fieldwork

4.1. Introduction

Field studies were completed in 2001 and 2002 as a portion of this research project, in order to gather information on the riprap. The main objectives of these field studies were to:

- measure the current size of riprap,
- compare data collected in this study to previous data, and
- determine if the riprap is disintegrating and where the disintegration is worst.

The first field study was completed between July 25 and August 7, 2001. Riprap particle sizes were measured in 2001 for the purpose of comparing these data with results of an earlier 1998 study and determine the amount of particle breakdown that had occurred within this time frame. The 1998 study was made available by the owner for this research in an unpublished consultant's report and is not listed in the references in order that the site is not disclosed. The second field study was completed between June 24 and 28, 2002. This field investigation was planned to improve the accuracy of the calculations for the masses of the rocks, to photograph the site, to confirm the existence of beached areas and to measure the rock sizes in these areas.

Each study consisted of measuring each piece of riprap within selected locations at intervals across the dyke system, as determined by the prior study completed in 1998. Additional pieces of riprap were selected at random positions along the dykes, measured and weighed to create a relationship for determining the mass of the measured riprap.

This chapter presents the riprap particle size data collected in July and August 2001 and in June 2002 at the site being studied for this research. This chapter also presents a comparison of the data and figures illustrating these results.

4.2. Scope of Analysis

This analysis consists of riprap measurements taken from selected locations at variable intervals across the dyke system during the field investigations conducted in 1998, 2001 and 2002. It includes the results of the measurements taken in 2001 and 2002 as well as a discussion of the possible interpretations gained from a comparison of the data accumulated in all three years.

Masses of selected samples of riprap were also measured to use as the source for creating a mass-to-measurement relationship. This relationship was used to determine properties such as the D_{50}, which is the size at which 50% of the mass of the riprap is smaller and is commonly used for measuring the average size of riprap.

This report provides the same data and calculations as specified by the ASTM Standard Test Method for Particle Size Analysis of Natural and Man-Made Riprap Materials (ASTM, 1994) while not following the procedure exactly. The procedure for the 2001 and 2002 fieldwork was based on the methods used in the 1998 unpublished report. This procedure deviates from the ASTM procedure as required by the constraints of the site and the nature of the riprap. These deviations are discussed in following paragraphs.

The ASTM procedure has 3 different test methods, Test Methods A, B and C, which are used for determining size-mass grading, size-range grading and mass-range grading respectively. Size-mass gradation is the standard method of determining the D_{50} of the riprap, which is the size at which 50% of the mass of the riprap is smaller, and is commonly used for measuring the average size of riprap. As a result, Test Method A has been followed as closely as possible.

The Test Method A requires the removal of a sample of the rock to a test location for sieve analysis (or other measurement method) and for mass determination. Each of the studies discussed in this report deviated from the standard procedure, since it is unacceptable in terms of both the costs involved and the safety of the dyke system to remove the riprap from the dyke. Instead, riprap larger than 0.2 metres was measured in place using a tape measure, as discussed in Section 4.3.2. In general, the riprap was not weighed, except for a sample amount of the rock as discussed in Section 4.3.5.

Section 5.4 of the ASTM procedure (ASTM, 1994) discusses recommended methods for the determination of mass using Test Method A. To convert the size measurements to mass, the procedure recommends the use of a figure provided by the ASTM standard that relates the clear square opening size to a mass using an assumed bulk specific gravity. (Bulk specific gravity is defined in section 5.3.1 of this research report.) Since the bulk specific gravity of limestone is lower than that listed in the standard (according to West, 1995), a deviation from the ASTM procedure was required and sample riprap pieces were selected across the dyke system for mass determination. The method of using these data for the determination of mass will be discussed further in section 4.3.5 of this report.

Section 5.4 of the ASTM standard also states that this method is useful only when the amounts of "slab" shaped pieces are not significant. In this study, the number of "slab" shaped pieces is significant (approximately 1 in 6 riprap pieces), so the method of dealing with these "slab" pieces will also be discussed further in section 4.7.1 of this report.

All three of the field studies use the method described in Section 4.3.2 and 4.3.3 to measure and describe riprap larger than 0.20 m on two sides, but estimates of percent voids and rocks smaller than 0.2 metres were done using different approaches. In the 1998 study, it appears that the study assumed 50% of each grid was covered by large riprap, so the remaining 50% was considered void space. The "percent of voids filled" was then taken as the proportion of the 50% void space that was covered by "small rock" (riprap pieces smaller than 0.2 metres on two sides). The mass of "small rock" was taken as the "percent of voids filled" times 50% voids times the total mass of the "large rock" (larger than 0.2 metres on two sides), at that grid. As will be explained Section 4.3.4, in 2001 and 2002 the "percent voids" was taken as the percent of the surface area of the grid not filled by rock larger than 0.1 m and a count was taken of the number of "small rocks". Since these methods vary considerably, these two properties (percent voids and small rock) will not be compared in this report.

The measured data for 1998, 2001, and 2002 have been compared in a variety of ways. The number of rocks, masses and sizes of the riprap pieces are compared. The data are also analysed as if the pieces of riprap have been subjected to a sieve analysis and the D_{50} values are compared by location across the dykes.

4.3. Site Investigation Procedure for 2001 Study

As discussed in previous sections, the site investigation procedure used in 2001 was modelled after the 1998 procedure. Individual pieces of riprap were measured and described, in designated sites across the dyke system and a number of rocks were selected and weighed. This section describes the procedures used in 2001 and how these procedures deviated from the 1998 study and the ASTM standard.

A recording sheet was created for each site, with the location, rock measurements, descriptions and other important information. Typed versions of the recording sheets are included in a compact disk, attached to this report. A sample is included as Figure 4.1.

4.3.1 Site Locations

The site locations for the 2001 study were based on those chosen for the 1998 study, so that riprap measurements in 2001 could be directly compared with the corresponding 1998 measurements.

At each site, a paint line was drawn around the edges of a 3 m x 3 m square or "grid". During the 2001 study, the 1998 sites were not precisely identifiable in most locations, as either the rocks had shifted or the paint was worn off. Where the 1998 grid was identifiable immediately by remnant paint marks, the locations were duplicated. Where there were no paint marks, the 2001 grid was located based on the station number and location on the bank. Sites labelled "lower" in the database indicate the bottom line of the grid was located within 1 metre of the fore-bay water elevation, while sites labelled "middle" indicate the grid was located approximately mid-slope of the dyke. In a small number of cases (two) where the amount of driftwood made the location dangerous or impossible to measure, the 2001 grid location was either repositioned or abandoned.

A digital photograph of each grid was taken with a round template placed within the grid for scale. These photographs are included in a compact disk, attached to this report. Separate files are provided for each grid site labelled by station location number. A sample photograph is included as Figure 4.2.

4.3.2 Measurement of Riprap Dimensions

The riprap within each grid was measured as if the dimensions could form a box enclosing each piece and the measurements were recorded on the recording sheet for that location. The longest face of each piece was measured, and then the other faces were measured at right angles to the longest. If a rock was partially buried, the length was measured as far as possible into the bank and an "E" for "Embedded" was noted beside that measurement. For the purposes of calculation in spreadsheets, this "E" was ignored and the dimension was taken as the length measured into the bank. After measurement and reporting of the dimensions, each riprap piece was marked with a small dot of paint to ensure it was not measured twice.

4.3.3 Riprap Descriptions

Each measured riprap piece was described with a colour, shape and other features useful to potentially group the riprap into similar categories. On the recording sheet for that location, these were recorded next to the measurements for that piece of riprap. In terms of colour, most riprap pieces were either whitish or yellowish. Some were pink or reddish, especially along bedding planes. The shape descriptions used are as follows:

- angular has no particular shape or is multi-faced,
- square has at least one face that is approximately square,
- rectangular has at least one face that is approximately rectangular,
- triangular has at least one face that is approximately triangular,
- cubic is approximately square on all faces,
- slab is flat on two parallel faces and usually relatively thin compared to its length, and
- rounded, meaning the edges and corners are rounded off.

The other features described are:

- fracturing is visible,
- bedding planes are visible on at least one face,
- porous, meaning there are visible holes in the rock, and
- fractured into pieces where two or more riprap pieces are recognised as being fragments of the same rock.

These descriptions are not used for any calculations, as it was felt that they are too subjective and are unlikely to relate to durability of the riprap. They were later used to aid the selection of sample pieces for weighing and laboratory testing. This ensured that pieces of each typical description were represented within the selected sample.

4.3.4 Small Rocks and Percent Voids

“Small rocks” are those smaller than 0.2 metres and larger than 0.1 metres on two sides. These were individually counted after the “large rocks” were measured, and the number recorded on the recording sheet for that location.

The “percent voids” was visually estimated as the percent of the area of grid not filled by rock larger than 0.10 m. The percent voids for each of the grids were recorded at the top of the recording sheet for that location.

4.3.5 Sample Riprap Masses

Masses of riprap pieces are required to determine the D_{50}, which is a standard method of assessing the average size of riprap on large dykes. The ASTM procedure (ASTM, 1994) recommends removal of all the riprap at each sample location and weighing each piece. As previously mentioned, this was unacceptable in this situation. The alternative method recommended by the ASTM procedure is to use the dimensions of the riprap in conjunction with a figure based on an assumed bulk specific gravity to determine the mass of each piece. According to West (1995), the bulk specific gravity of limestone varies between 2.19 and 2.60. This range is significantly broad and its higher end is still lower that that of most other rock commonly used for riprap (between 2.60 and 2.80). This approach was not considered appropriate.

As a result, sample pieces of riprap across the dyke system were measured and weighed to develop a correlation between the sizes of the riprap and their masses. These pieces were selected based on the relative ease with which they could be removed from the dyke, the maximum mass allowance of the scale used, and on their physical features, to ensure each general category of riprap was represented in the study. The pieces were removed temporarily from their locations, measured, weighed, photographed, and returned to their original locations. These photographs are included on the compact disk attached to this report.

4.4. Results of 2001 Site Investigation

4.4.1 Measured Rock at Grid Locations

The 2001 site investigation was undertaken between July 25 and August 7, 2001. In total, 3,324 riprap pieces were measured at 80 grid sites across the dyke system. Two of the 1998 grid sites were abandoned (the 1998 study has 82 sites), as the amount of driftwood created unsafe working conditions. For each grid site, an Excel file was created and named by the grid location. These files include a list of the three measurements and descriptions of each rock, the number of small rocks counted, the percent voids and basic information about that grid site. The files are included on the enclosed compact disk under a folder labelled Riprap Measurement Data and a sample is included in Figure 4.1.

The number of riprap pieces per grid location varied considerably. The number of "large" riprap pieces (larger than 0.20 m on two sides) measured at each grid site ranged from 16 to 68, with an average of 43 pieces per site. A total of 2687 "small" pieces of riprap (between 0.10 and 0.20 metres on two sides) were counted, in the 2001 study. The numbers ranged from 7 to 71 pieces on a grid site, with an average of 36 pieces per site.

The sizes of the riprap and percent void space at each grid also varied considerably. The largest pieces had long measurements reaching just over 2 metres in length. The average nominal diameter over the whole data set of riprap was 0.33 metres. The percent of voids ranged from less than 5% to 90%.

4.4.2 Weighed Samples

During the site investigation, 7 pieces of riprap were weighed and measured. The riprap selected had to be removable from the dyke by hand and had to be within the limits of the available weigh-scale. The riprap pieces weighed ranged in size from 40.7 kg to 93.1 kg, which was near the top limit of the scale. These riprap pieces varied in average nominal diameter from 0.18 to 0.41 metres.

One rock was removed from this data set, as the written data were not consistent with the corresponding photograph. When this rock was noticed as lying outside the typical rock curve, its photograph was checked and the measurements were evaluated. One of the measurements was obviously wrong (possibly the numbers were written backwards) according to visual inspection of the photograph.

4.5. Site Investigation Procedure for 2002 Study

The site investigation procedure used in 2002 was designed to photograph the dykes, verify rock measurements at previously recorded grids, confirm observations of beaching, and improve the accuracy of the mass calculations. Individual pieces of riprap were measured and described, at selected sites across the dyke system, in the same manner as in the 2001 study. Rock masses were taken, in this case using a crane, so larger rocks were weighed than in other years. This section describes the procedures used in 2002 and how these procedures deviated from the 2001 study.

4.5.1 Photographs

A tour of the dyke system was taken by boat and photographs were taken to provide a photograph library of the site. Photographs were taken of typical dyke sections and to show variation in the typical sections. Any evidence of beaching was also photographed.

4.5.2 Site Locations

Originally, the sites were chosen to verify previous grid measurements and to confirm evidence of beaching. During the field investigation, it was found that many of the sites chosen, based on expected evidence of beaching, had been remediated with large granite boulders. As a result, many of the originally chosen sites were not measured or were moved to a slightly different location along the dyke.

A digital photograph of each grid was taken with a clipboard placed within the grid for scale. These photographs are included in a compact disk, attached to this report and are labelled by station location number.

4.5.3 Measurement and Description of Riprap

Within each grid completed during this study, the riprap pieces were measured and described, and the void ratio estimated, as discussed in sections 4.3.2 through 4.3.4.

4.5.4 Sample Riprap Masses

Masses of riprap pieces are required to determine the D_{50}, which is a standard method of assessing the average size of riprap on large dykes such as the one being studied. During the previous studies the riprap was lifted by hand, so the sizes were restricted to what could be carried (approximate maximum of 100 kg). In the 2002 field study a crane was used to lift significantly larger rocks.

The rocks weighed in 2002 were limited by the capabilities of the crane. Since the crane was very large and not very mobile on the dyke system, the rocks weighed were limited to a small area. The scale on the crane had a very large error range of plus or minus 45 kilograms, therefore only rocks masses of at least 400 kilograms were used for the mass determination calculations. A variety of very large rocks encompassing the major types were found and weighed within the area the crane could reach. The pieces were removed temporarily from their locations, measured, weighed, photographed, and returned to their original locations. These photographs are included on the compact disk attached to this report.

4.6. Results of the 2002 Site Investigation

4.6.1 Photographs

Over the course of the boat trip, 328 photographs were taken. These were used to create a significant photographic library, which is included on the attached compact disk in the folder titled Photographs.

4.6.2 Measured Rock at Grid Locations

The 2002 site investigation was undertaken between June 24 and 28, 2002. In total, 564 riprap pieces were measured at 14 grid sites across the dyke system. For each grid site, a Microsoft Excel file was created and named by the grid location. As in the 2001 study, the recorded data include a list of the three measurements and descriptions of each rock, the number of small rocks counted, the percent voids and basic information about that grid site. These files are included on the enclosed compact disk under a folder labelled Riprap Data.

The number of riprap pieces per grid location varied considerably. The number of “large” riprap pieces (larger than 0.20 m on two sides) measured at each grid site ranges from 25 to 50, with an average of 40 pieces per site. A total of 547 “small” pieces of riprap (between 0.10 and 0.20 metres on two sides) was counted, in the 2002 study. The numbers ranged from 11 to 63 pieces on a grid site, with an average of 39 pieces per site.

The sizes of the riprap pieces and percent void space at each grid also varied considerably. The largest pieces had long measurements reaching just over 1.7 metres in length. The average nominal diameter over the whole data set of riprap was 0.30 metres. The percent of voids ranged from less than 5% to 50%.

4.6.3 Weighed Samples

During the site investigation, 18 pieces of riprap were weighed and measured. The riprap selected had to be removable from the dyke by crane and had to be large enough that the margin of error was acceptable. The riprap pieces ranged in mass from 408 kg to 1588 kg, with an error margin of plus or minus 45 kg. These riprap pieces varied in average nominal diameter from 0.53 to 0.99 metres. These additional masses represent a significant enlargement of the previous database on rock masses.

4.7. Particle Size-Mass Grading

An important property in designing riprap is the D_{50}, the rock size at which 50% of the riprap is smaller by mass. This property is often used as a guide for establishing the design average size for riprap. In normal soils, D_{50} is determined by carrying out a size-mass grading usually using the results of a sieve analysis. At the site being studied for this research, a sieve analysis is not possible, given the size of the rock pieces and the physical problem of handling large numbers of large rock pieces. The size-mass grading was therefore carried out using the dimensions of the rock and calculating a mass for each rock based on these dimensions and an assumed mass density. Since the 2001 site investigation collected mass data on only 7 rock pieces, the data from the 1998 were combined with the 2001 data to create a sample size of 27 pieces. The 2002 site investigation increased this number by 18, to a total of 45 pieces.

The ASTM standard (ASTM, 1994) recommends using a graph of sieve opening size versus mass as the method for determining the calculated masses of riprap pieces not weighed. The riprap at this site is limestone and likely has a different sieve opening size to mass than that indicated by the ASTM graph. The ASTM also states this graph is only useful where slabs are not significant. Since there are a significant number of slabs at this site, the riprap was divided into two shapes, namely “slabs” and “typical” rock pieces. Different methods of calculating mass were explored for each of these shapes

4.7.1 Determination of Riprap Shape and Mass

The shapes of the riprap at the site being studied are extremely variable, making volume and mass calculations difficult. As previously mentioned, the “slab”-shaped pieces were so designated on the basis of the ratio of their longest to shortest measurements. Those riprap pieces with a longest/shortest ratio greater than 4:1 were considered “slabs”, while the rest were considered “typical” riprap pieces. This 4:1 ratio was chosen as it was mentioned in the ASTM standard (ASTM, 1994) as a typical ratio for slabs.

To determine the volume of the riprap, the slabs were calculated as boxes (length x width x breadth), while the “typical” riprap pieces were calculated as midway between a box and a sphere. The volume of the “typical” pieces was calculated in two ways, the volume of a box (length x width x breadth), and the volume of an equivalent sphere (π x diameter^3 / 6, where diameter = cube root (length x width x breadth)). The two resulting volume estimates were then simply averaged for each “typical” riprap piece.

The mass was determined by multiplying the volume by the assumed mass density of the limestone (2611 kg/m^3). The calculated masses were then compared to the measured masses (see Figure 4.3). (The R^2 value indicates how closely the trend line corresponds to the actual data. It generally varies from

0 to 1 and indicates a close fit when it is at or near 1.) The outlying rocks occur because their shape varies so much relative to their outer dimensions.

Since the "typical" rock shapes vary considerably and are measured by their outer dimensions, the actual mass is generally lower than found by multiplying the volume by the density of limestone (2611 kg/m^3). The ASTM procedure (ASTM, 1994) recommends using their sieve opening size versus mass figure, so a similar sieve opening to mass figure was created based on the intermediate dimension and the measured mass of the riprap. This can be seen in Figure 4.4. (This figure shows only typical pieces of riprap and does not include slab shaped pieces.) The use of this figure is based on an assumption that the intermediate dimension (width) better defines the properties of the riprap, rather than the largest dimension (length). The correlation between the intermediate dimension and the measured mass was not acceptable when the intercept of the slope was drawn through zero (0,0). A best-fit line was produced, but the intercept passed through 29.07 cm, which seems unacceptably high.

A figure, of nominal diameter versus mass, produced similar results that can be seen in Figure 4.5. (Again, only typical pieces of riprap are compared in this graph.) The nominal diameter is calculated by taking the cube root of the multiplication of the 3 dimensions of each riprap piece.

Up to this point, the best correlation was the assumed calculated mass, based on the volume midway between a box and a sphere multiplied by the density, as can be seen in Figure 4.3.

Figure 4.6 shows the relationship produced by analysing the "slabs" and "typical" rocks as one data set. As can be seen in Figure 4.7, this produces a better correlation than taking the data individually (i.e. multiplying the calculated "slab" masses by the slope of the line for "slabs" found in Figure 4.3, and "typical" masses by the slope of the "typical" line in Figure 4.3). As a result, the relationship found in Figure 4.6 is used throughout the rest of the calculations.

Figure 4.8 has been included to show the difference between mass data collected in 1998, 2001 and 2002. The data for this figure are calculated in the same way as in Figure 4.6. While both the 1998 and 2001 data sets produce a low correlation, the 2001 data produces an especially low correlation, as seen by the negative R^2 value. The rock weighed in 2001 tended to be larger than those weighed in 1998, but it still did not nearly cover the range of possible rock sizes on the dyke system. The 2002 data set produced a significantly better correlation and when added to the previous data, almost the entire range of possible rock sizes has been measured.

4.7.2 Sieve Analysis Calculations and D_{50}

For the sieve analysis calculations, the percent retained was calculated in a way as similar as possible to what would be done if the riprap in each grid had undergone a sieve analysis. Each riprap piece was grouped into theoretical sieve sizes based on its intermediate dimensions. For each theoretical sieve size, the mass of each piece was calculated using the relationship found in Figure 4.6 and the total sum of masses was found. The percent passing each theoretical sieve size was calculated and graphed as shown in Figure 4.9.

These calculations are used to determine the D_{50}, that is the diameter of the theoretical sieve that would allow 50% of the calculated mass of riprap to pass (or be retained), of each grid. As can be seen in Figure 4.9, the D_{50} can be found by finding the sieve size (intermediate dimension) where the line used for modelling the data points crosses grid line for 50% passing.

4.8. Discussion and Comparison

4.8.1 2001 Study

There appear to be some systematic relationships between the measured data and their location along the dyke system. Those locations that are most exposed to large fetches appear to have different properties than those located where the dyke is more sheltered from wind and waves. There also appear to be inverse relationships between the number of rocks measured on a grid and the percent of void space.

Figures 4.10.a through c show the number of “large” and “small” rock (riprap pieces greater than 0.2 m on two sides and smaller than 0.2 m, respectively), while Figures 4.11.a through c show the percent of void space at each grid site. In most cases the number of large rocks appears to be inversely related to the percent voids. The higher the number of large rocks the lower the percent voids. The correlation between these numbers and the location (exposure to fetch) along the dyke is not clear. The more exposed areas, which tend to be towards the outer stations (dykes 3 and 4 South, and dyke 2 North), seem to have a greater number of large rocks and seem to have a lower percent voids.

There is a possible relationship between “small” rock (referring to riprap pieces between 0.1 and 0.2 m on two sides), large rock and location. Figures 4.10.a through c indicate that the number of small rocks and large rocks both increase with exposure (with, perhaps, the exception of dyke 4 South).

These data by themselves do not prove conclusively that the riprap is experiencing degradation. The fact that the more exposed areas of the dyke have a greater number of large riprap pieces and small riprap pieces seems to show that the exposure contributes to the protection of the dyke. This should not be the case, and may indicate observer errors in the field. An alternative explanation, and one which the author favours, is that the larger pieces of riprap break down into smaller riprap, but that only a small portion of that broken riprap is actually smaller than 0.2 metres on two sides. This would mean more large rocks in general, but that the average size of these "large" rocks is smaller. Comparison with earlier data from 1998 is required to show if this is true.

4.8.2 Comparison of 1998 and 2001 Data

Once the 1998 data are introduced into the study, differences can be seen in the number and size of rock measured in each study. Since small pieces of riprap and percent voids were treated differently in the two studies, these data will not be included in the comparisons described in following paragraphs.

Comparison of the number of large rocks in the 1998 and 2001 studies produce the interesting results shown in Figures 4.12.a through c. The number of large rocks in the 2001 study appears to be greater than the corresponding number reported in the 1998 study by as much as 2 to 3 rocks per square metre in certain areas of the dykes such as dyke 2 South and dyke 2 North. The fetch distance at these dykes is longer than at dykes such as dyke 1 South and dyke 1 North. This could lead to the conclusion that the observers in the two studies used slightly different procedures and measured different numbers of rocks. However, it will be remembered that the *number* of large rocks is not in itself a reflection of an ability to provide protection against wave action. The *size* of the rocks is actually more indicative of potential break down of the rock pieces.

Meanwhile, in more protected areas, the number of large rocks in each grid appears to be greater in 1998 or similar.

The data for average nominal diameters (Figures 4.13.a through c) indicate the average nominal diameter of the rock measured in 2001 is smaller by up to 0.08 m than measured in 1998. These differences are more apparent in more exposed sites (dykes 3 and 4 South, dyke 2 North) and less apparent in more protected areas (dyke 1 South and dyke1 North). These differences reach 0.08 metres in areas of the North dyke with Southwest exposure.

Meanwhile, the D_{50} from the size-mass grading data does not show the corresponding reduction in size, that might be expected from average nominal diameter data, such as those obtained from Figure 4.9. These data are shown in Figures 4.14.a through c and appear somewhat inconsistent. One explanation, relating to the assumption that the slabs break up along weak planes, could explain these apparent contradictions. In this case, the number of riprap pieces could increase in areas with more exposure, as the large pieces break up into many smaller pieces, but still with nominal sizes larger than 0.2 metres. The average nominal diameter would be smaller, but the D_{50} may remain the same. Cracking along the bedding planes may create two pieces of riprap, each of which would have the same median dimensions as the original rock.

Although splitting along bedding planes may affect the total number of riprap pieces and average nominal diameter, it is not likely the governing factor. Since the proportion of "slabs" in the riprap is only 1 in 6, the "typical" riprap pieces should also contribute to the disintegration patterns and some decrease in D_{50} would be expected. According to the field results in the attached compact disk, "typical" riprap was noted on occasion to be in the process of fracturing and to be rounded, meaning that the overall size and D_{50} should be reducing.

4.8.3 Comparison of 1998, 2001 and 2002 Data

As a result of the remediation efforts by the owner, the number of locations measured in the 2002 study were reduced from the number planned, but these still show some interesting results when data collected throughout the three studies is compared.

As can be seen in Figures 4.15.a through c and Figure 4.16, it appears that the average mass of the rocks is decreasing. The number of sites measured in 2002 is significantly less compared to those measured in previous years, but the trend appears to continue to 2002. The total mass of the rocks at a site increases with the total number of rocks, as is expected.

This total mass of rocks at a site is related to, but not the same, as the average size of the rocks at that site. It is interesting to note that the D_{50} appears to also be decreasing, as seen in Figure 4.17. This decrease is not nearly as dramatic as the total mass, but it is apparent between the 1998 and 2001 studies. Due to the fact that there are so few sites measured in the 2002 study, the trend line is significantly altered by one site at which the D_{50} is considerably higher than the rest. Remember that the D_{50} is directly related to the intermediate dimension of the rocks at that site. Note that the 1998 and 2001 studies show a similar site, but this one site does not significantly alter the trend in those data.

The average nominal diameter of the rocks appears to indicate a decrease in size of the rocks over all three years (Figure 4.18). In this case, the data are not dependent on one dimension of the rock, but all three and the data do not have the same out-lying points as the D_{50} data. It is interesting to note the D_{50} and average nominal diameter in all three years indicate that the size of the rocks decreases at sites with a larger number of rocks. This seems to indicate that at least some of the rocks are breaking down into two or more rocks that are still large enough to meet the measurement criteria for "large" rocks.

Comparisons of the data based on the height of the grid (lower, middle, and upper) on the dyke, did not result in any obvious associations. For the ease of reading this report, these graphs have not been included.

Although the comparisons based on height of the grid did not indicate a difference in the breakdown of rocks based on the location of the rocks, the photographic evidence shows some beaching along most of the dykes. This can be seen in Figure 4.19, which shows beaching occurring along the elevation of the summer water level, indicating that wet-dry cycles and low-energy waves affect the rock.

4.9. Conclusion

The field studies show evidence of some fracturing and disintegration of the riprap at some locations along the dykes at this site. The number of large rocks, defined here as a nominal size greater than 0.2 metres, along the dykes appears to be greater in areas of more exposure to wind and fetch distance. The D_{50} has not changed significantly in most areas, while the average nominal diameter in areas exposed to longer fetch distances has reduced between 1998 and 2001. These apparent discrepancies in the results of the study can be explained if it is assumed most of the disintegrating rock breaks up in such a way that the median dimension remains constant.

"Slab" shaped riprap pieces, which are most likely to break down in this way, account for approximately 1 in 6 pieces of riprap. The proposed mechanism for explaining the observations works well if it is assumed that the riprap is comprised mainly of "slab" pieces and that "slab" pieces break down, while "typical" pieces remain whole.

The evidence for riprap disintegration is not totally clear at this time. Certain relationships appear to show the riprap is breaking down, while other relationships show very little disintegration. Meanwhile, visual evidence from field inspections and photographs show beaching formations in some areas. Laboratory testing is necessary to obtain evidence indicating the dominant disintegration processes.

2001 Riprap Measurement Program

Dyke		Station	Location
2	South	79 + .00	Middle

Percent Voids 40%
Number of small rocks 65
Number of large rocks 46

Comments:

Measurements (cm)			**Descriptions**
31	28	8	White Angular Slab Fractured
26	45	10	White Angular Slab Fractured
29	25	6	White Angular Slab
37	26	14	Yellow White Porous Rounded
63	59	35	**Red and Black Granite
45	60	35	White Angular Fractured Embedded
51	40	14	Yellow Porous Rounded
42	23	8	White Angular Slab Fractured
31	38	71	Yellow Angular Porous Fractured
37	23	16	Yellow White Rectangular Porous Fractured
42	20	16	White Angular Fractured
29	41	12	White Angular Fractured
29	38	16	Yellow Angular Fractured
20	28	80	White Angular Fractured
42	44	15	White Angular Slab
20	28	4	White Angular Fractured
9	32	21	Yellow White Angular Porous Fractured
50	59	8	White Angular Slab Fractured
38	28	19	Yellow Angular
46	25	29	White Angular Fractured
23	25	16	White Angular Fractured
84	26	53	Yellow Angular Porous Fractured With Bedding Planes
33	40	5	White Angular Slab
30	34	8	White Angular Fractured Embedded
33	32	17	Yellow Angular Fractured
24	48	11	White Angular Slab Fractured
22	29	12	White Angular Slab
22	26	10	White Square Fractured
26	33	12	White Angular Fractured
42	27	6	White Angular Fractured
22	37	10	White Angular Fractured
35	46	23	Yellow Cubic
37	46	10	White Angular Fractured
32	22	17	Yellow Angular
53	21	25	White Angular Embedded
22	16	34	White Angular Rectangular Fractured
73	49	17	White Angular Fractured
40	35	18	White Angular Fractured
39	37	10	White Angular Fractured
21	30	14	White Angular
24	28	12	White Slab Rectangular
49	40	11	Yellow Angular Slab Fractured
26	39	14	White Angular Fractured
56	39	15	White Angular Fractured
21	22	16	White Angular Rectangular
21	26	5	White Angular Slab Fractured

Figure 4.1 Typed Sample of Recording Sheet

Figure 4.2 Photograph of Grid - Dyke 2 South, Station 79+00 (Middle)

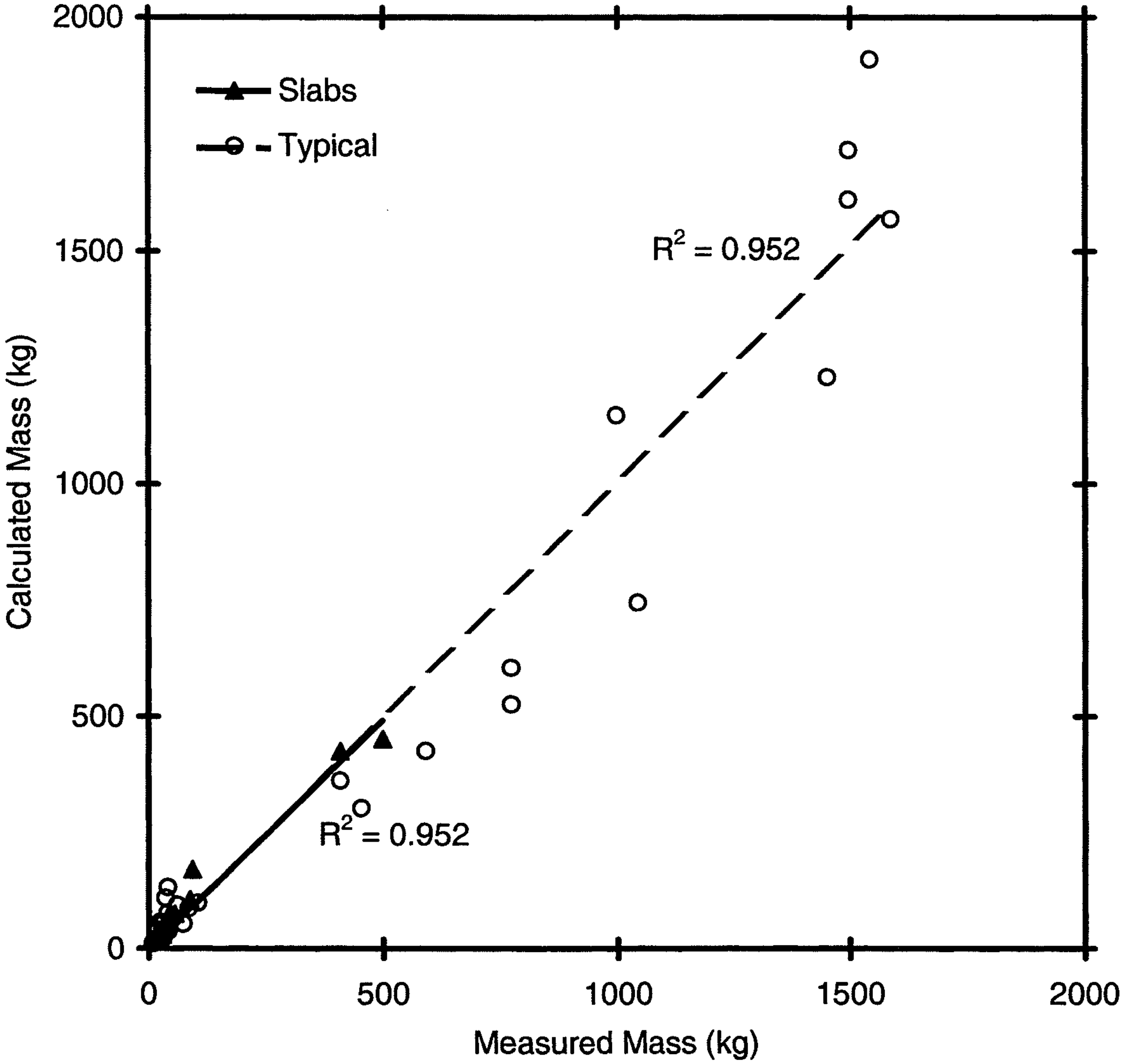

Figure 4.3 Measured versus Calculated Mass for Slabs and Typical Rocks

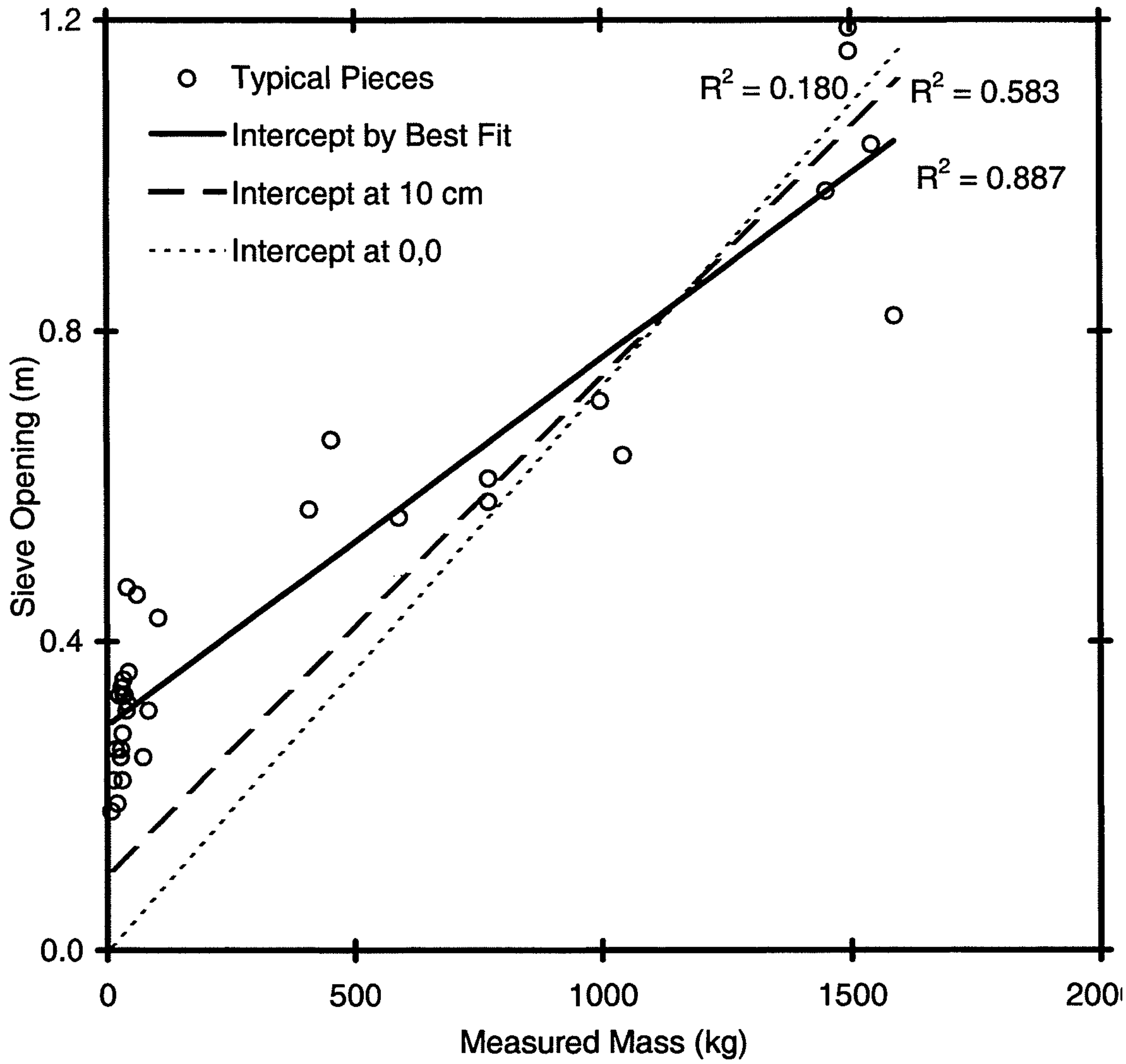

Figure 4.4 Measured Mass versus Sieve Opening Size for Typical Riprap Pieces

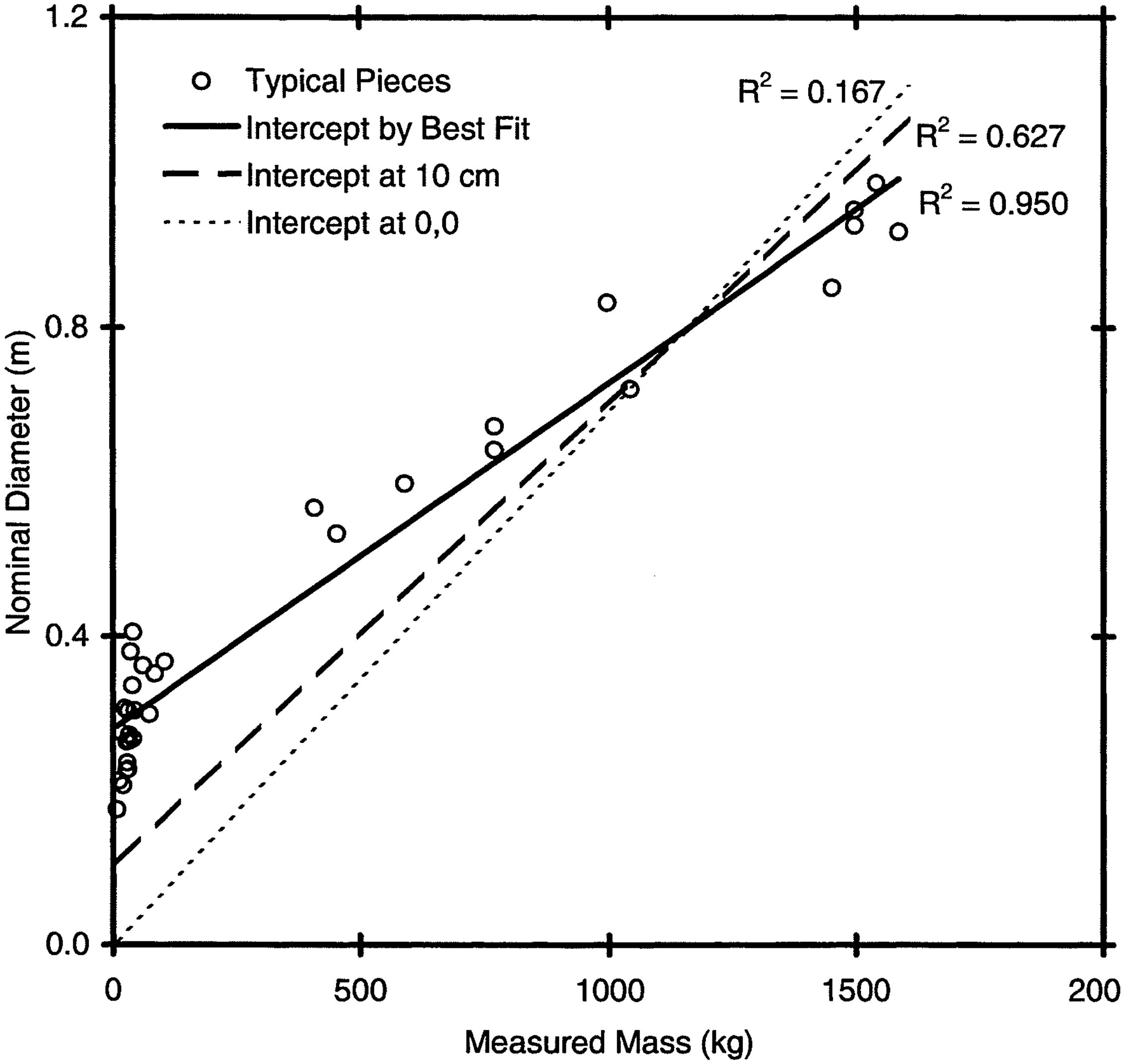

Figure 4.5 Measured Mass versus Nominal Diameter for Typical Riprap Pieces

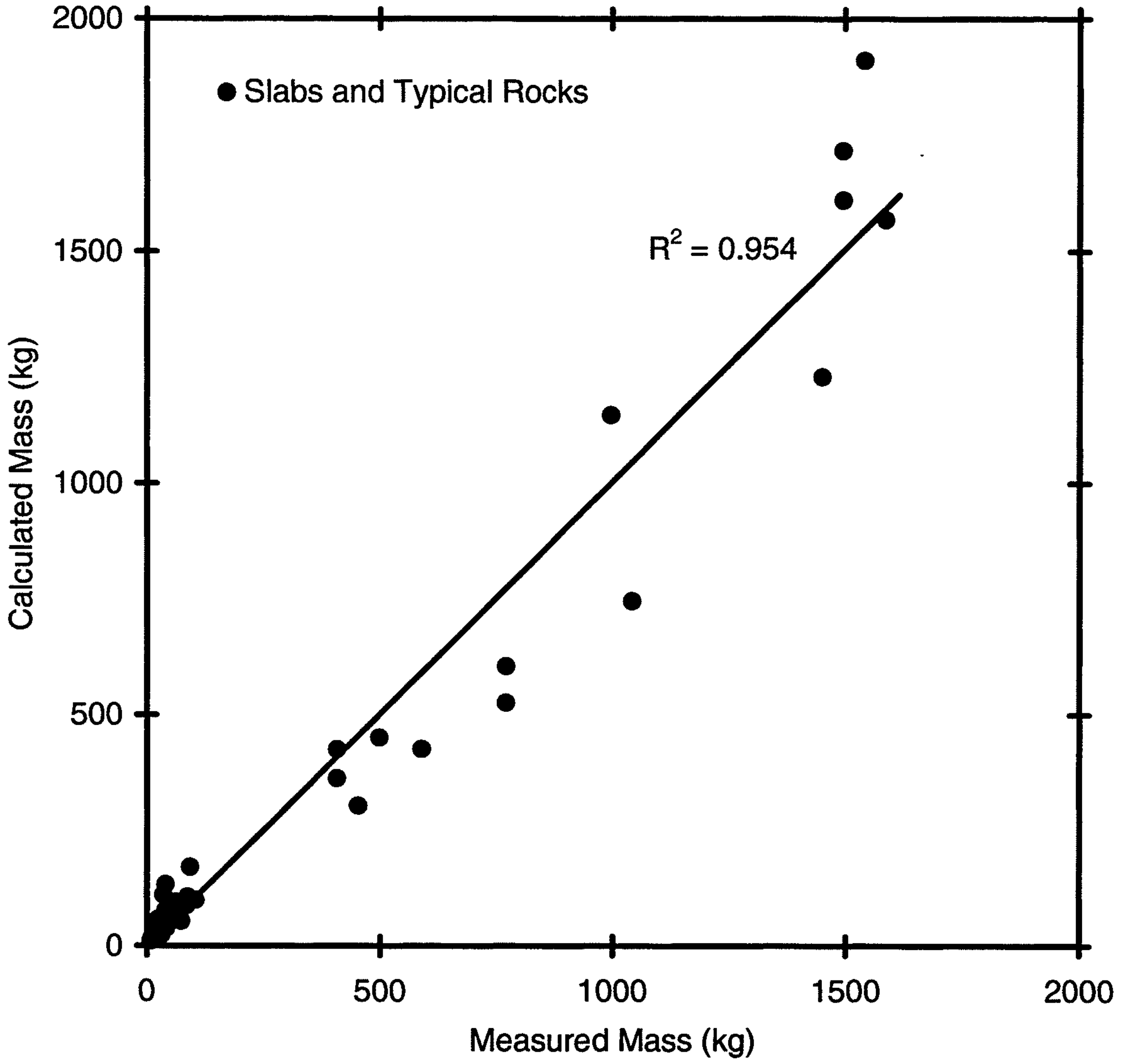

Figure 4.6 Measured Mass versus Calculated Mass for Slabs and Typical Rocks as One Data Set

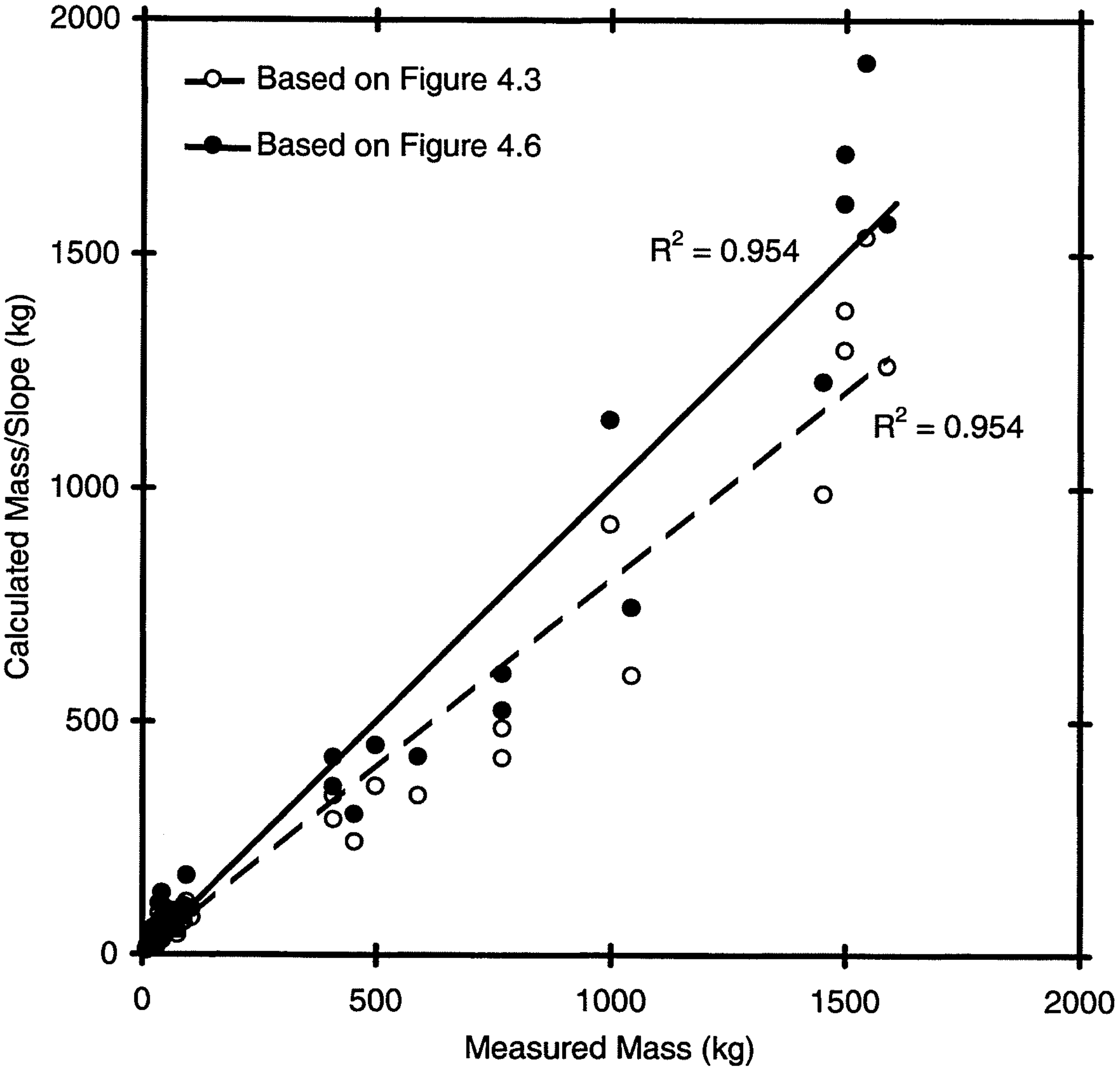

Figure 4.7 Measured Mass versus Calculated Mass/Slope for Slabs and Typical Rocks

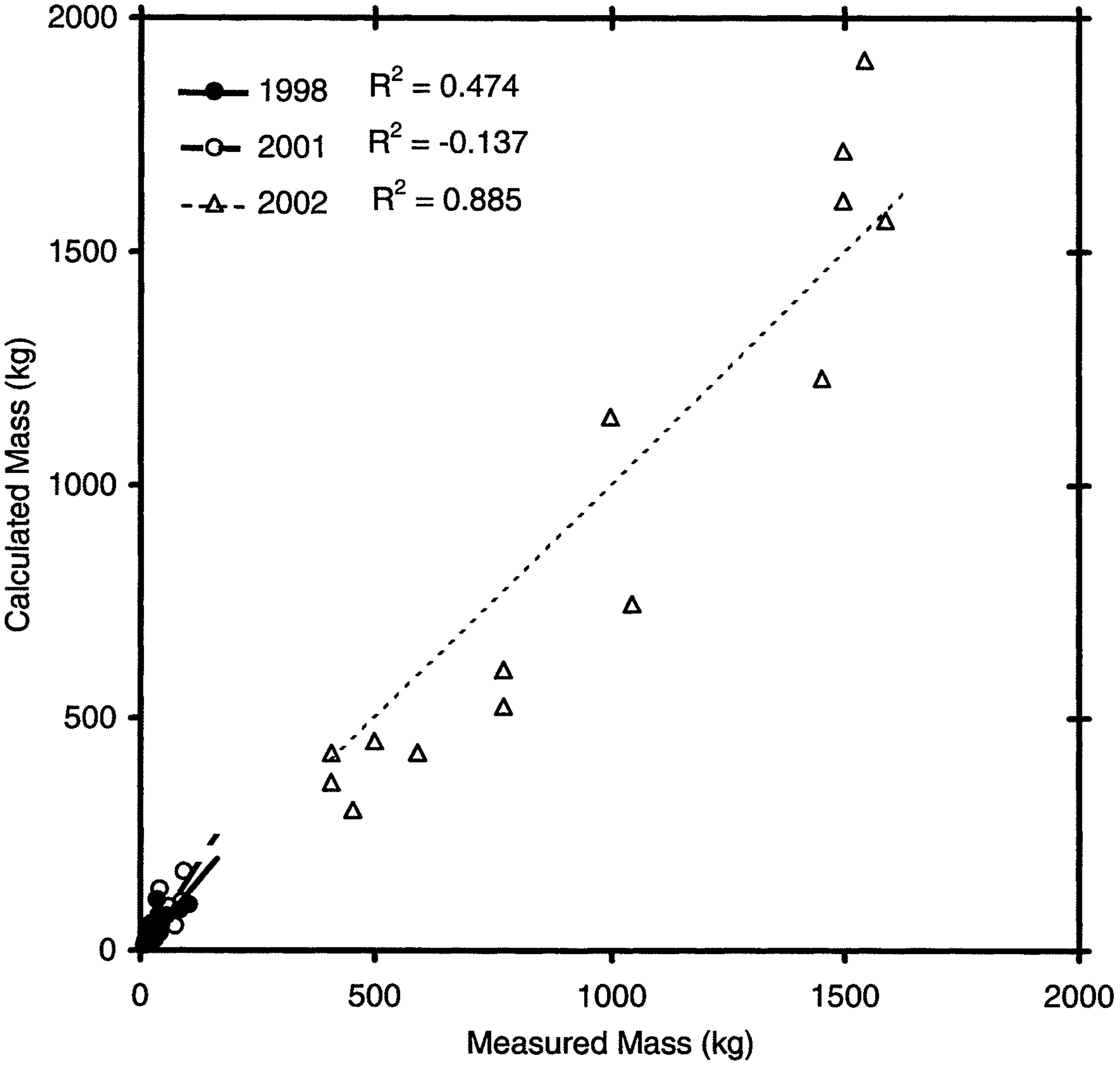

Figure 4.8 Measured Mass versus Calculated Mass for 1998, 2001 and 2002 Data

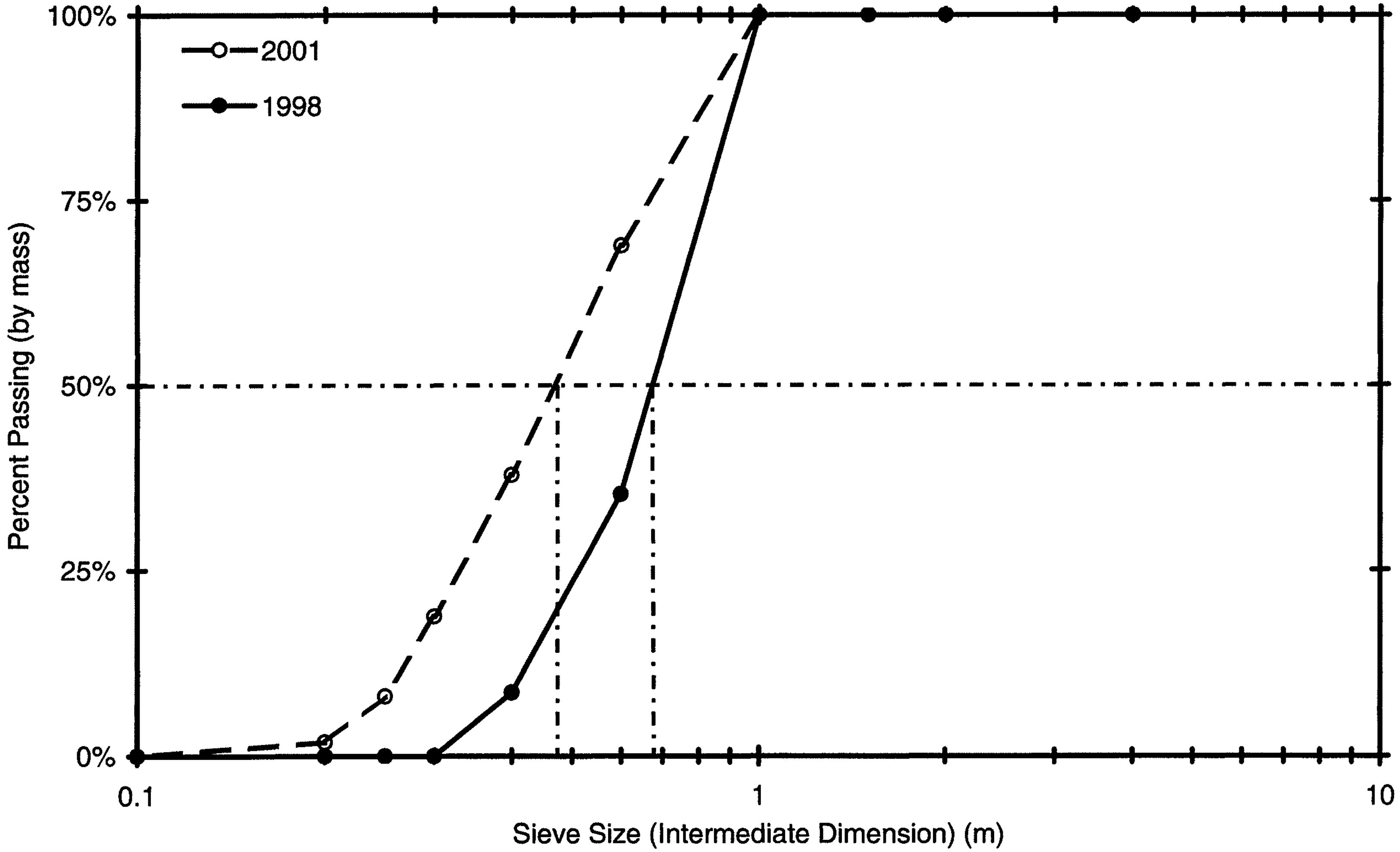

Figure 4.9 Size-Mass grading Sample – Dyke 2 South, Station 79+00

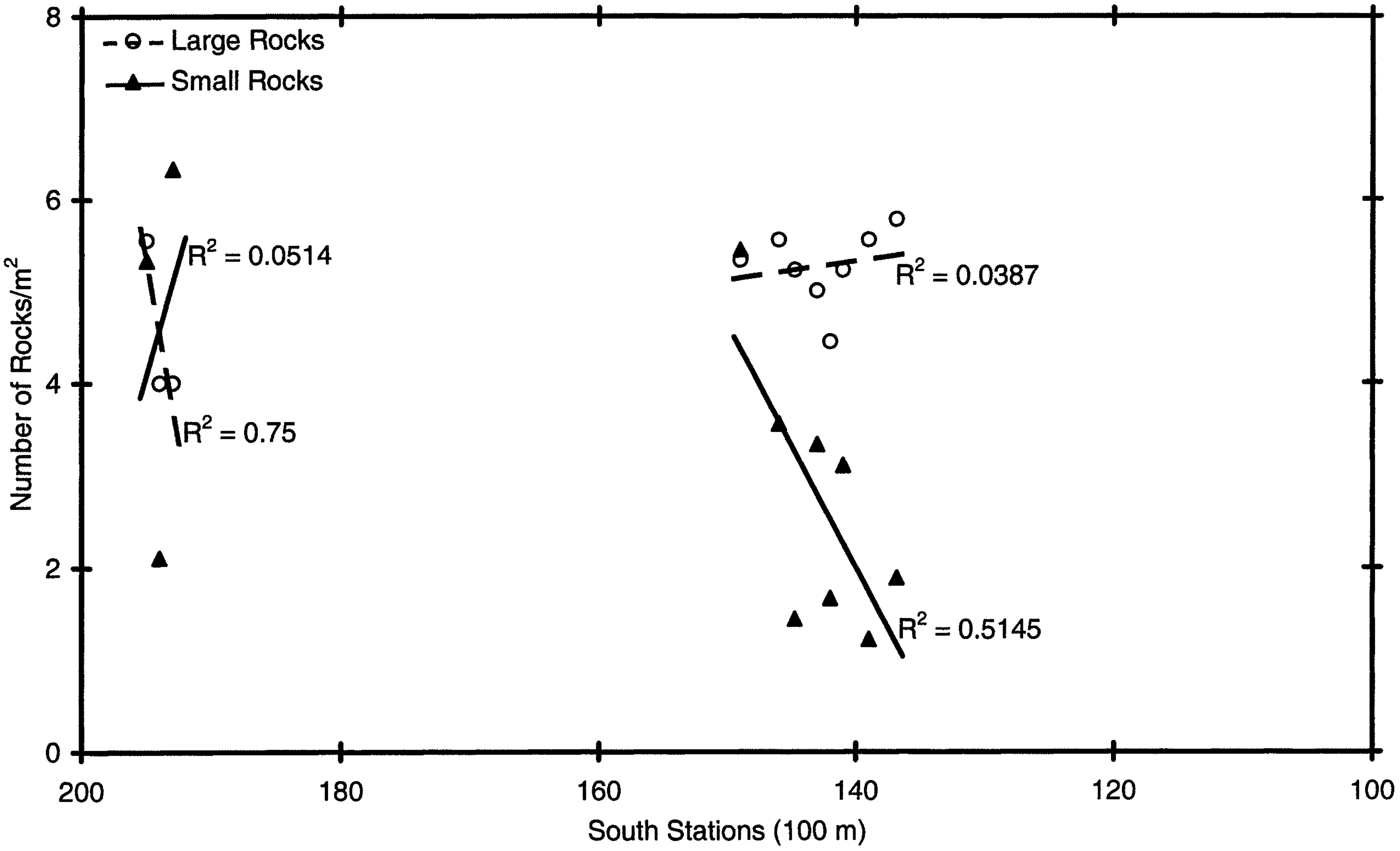

Figure 4.10.a Number of Rocks, 2001, Dykes 3 and 4 South

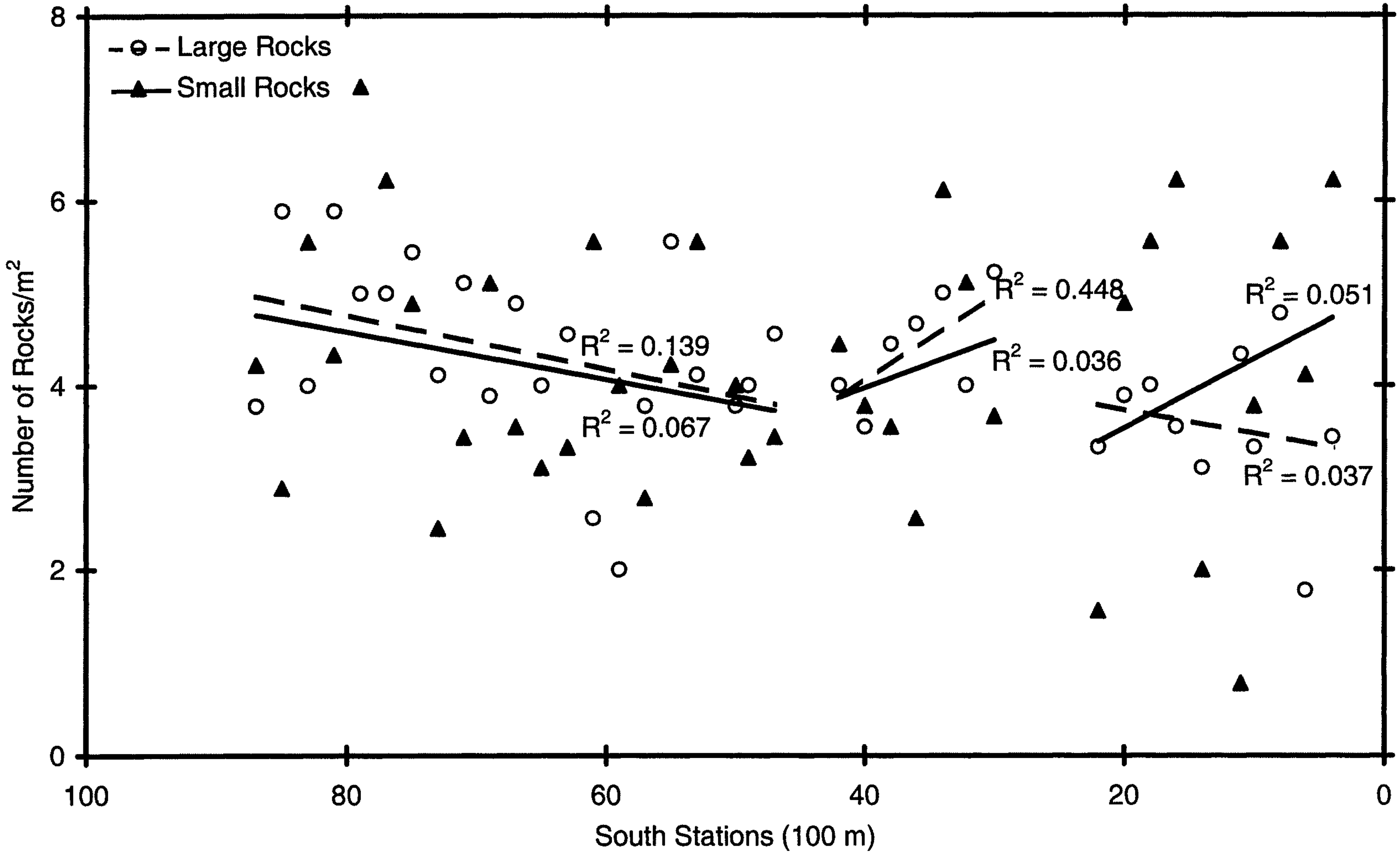

Figure 4.10.b Number of Rocks, 2001, Dykes 1 and 2 South

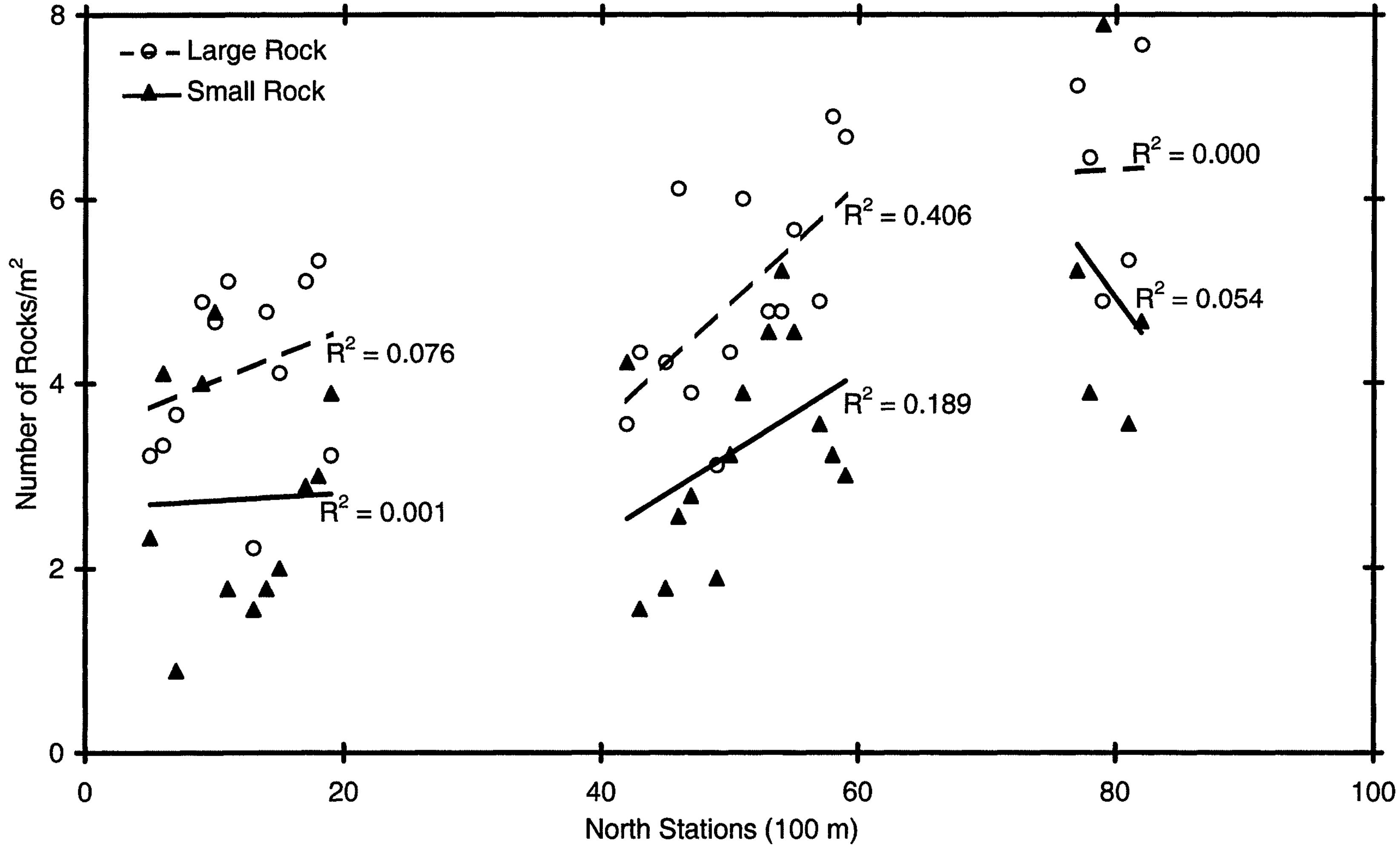

Figure 4.10.c Number of Rocks, 2001, Dykes 1 and 2 North

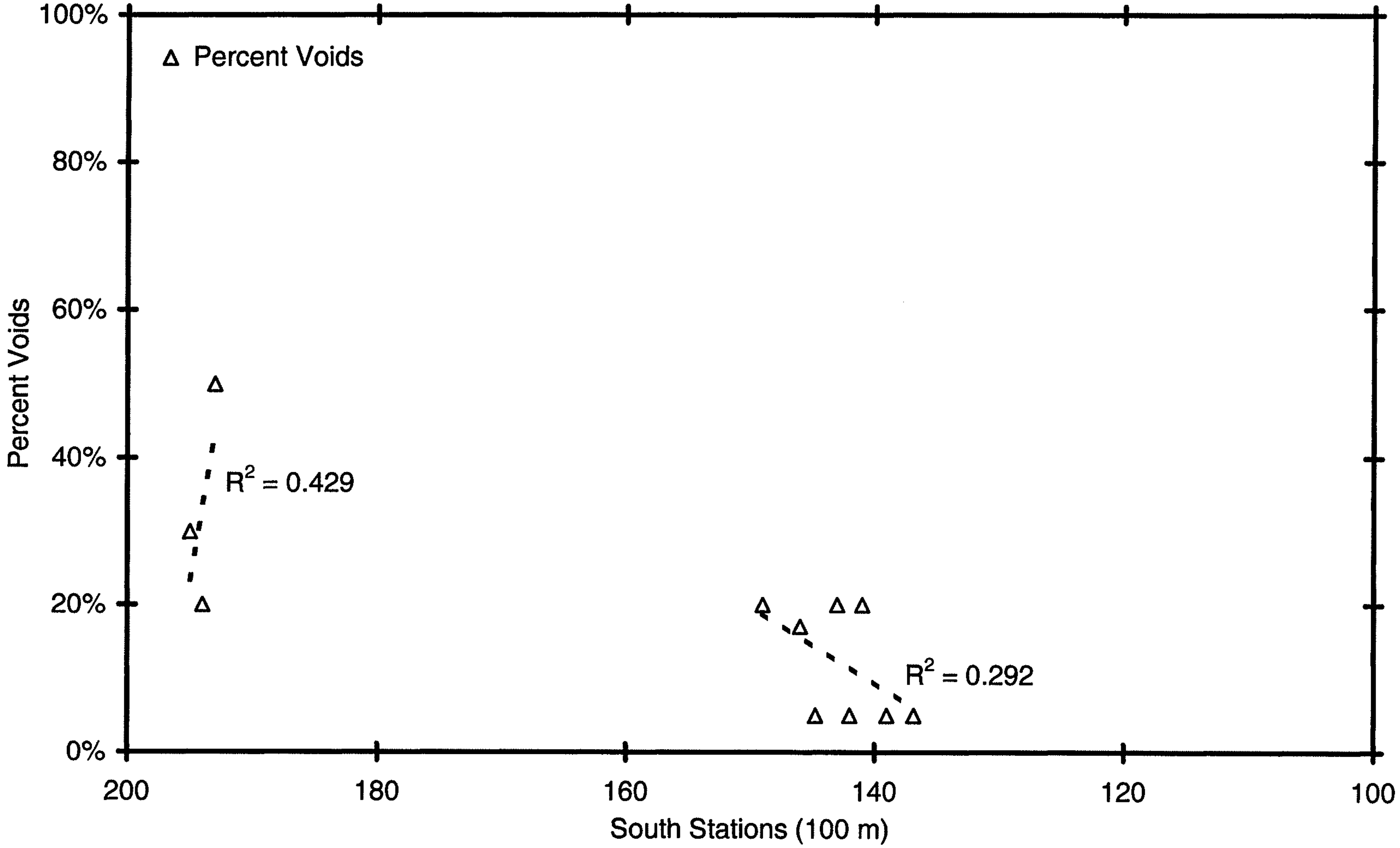

Figure 4.11.a Percent Voids, 2001, Dykes 3 and 4 South

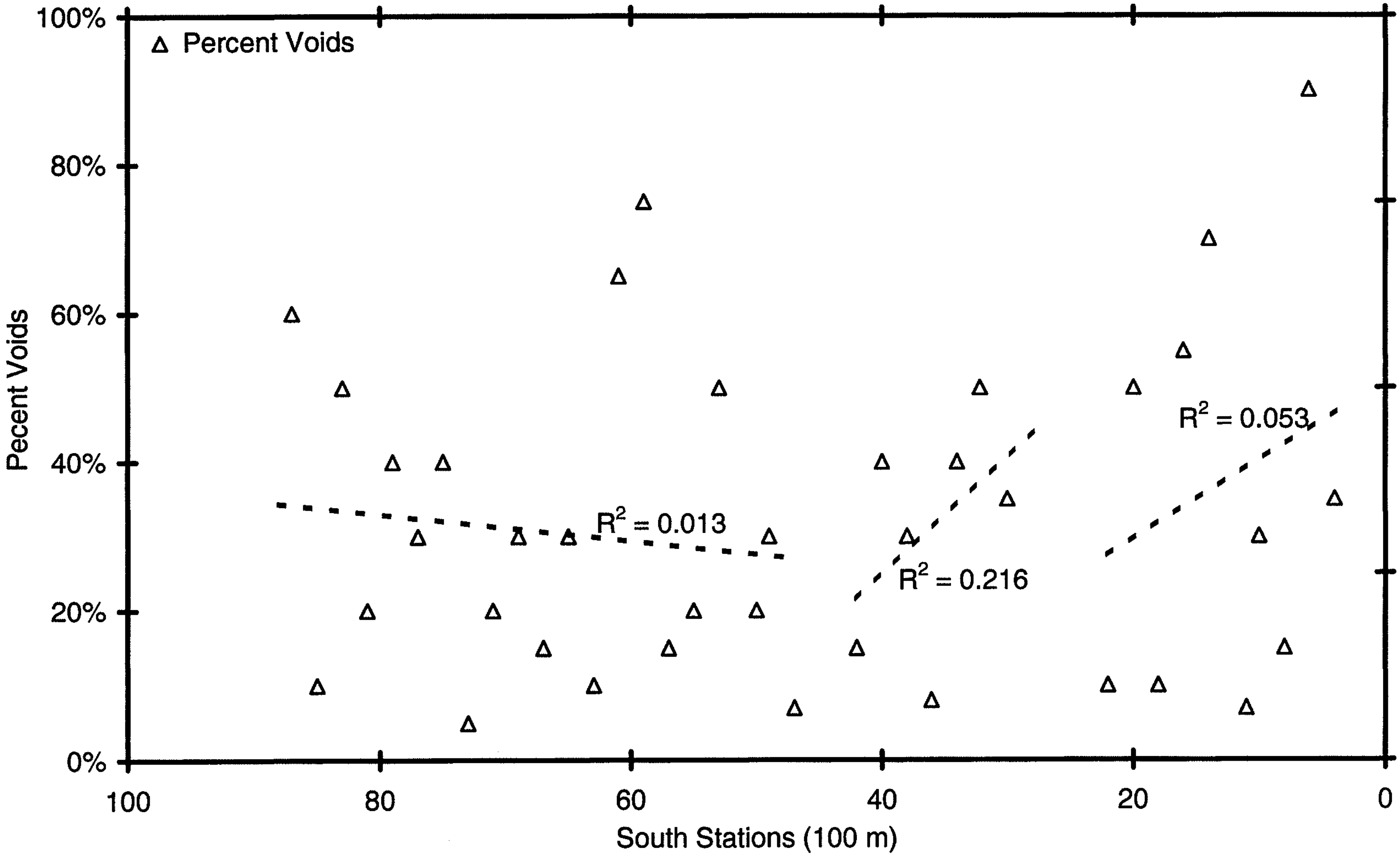

Figure 4.11.b Percent Voids, 2001, Dykes 1 and 2 South

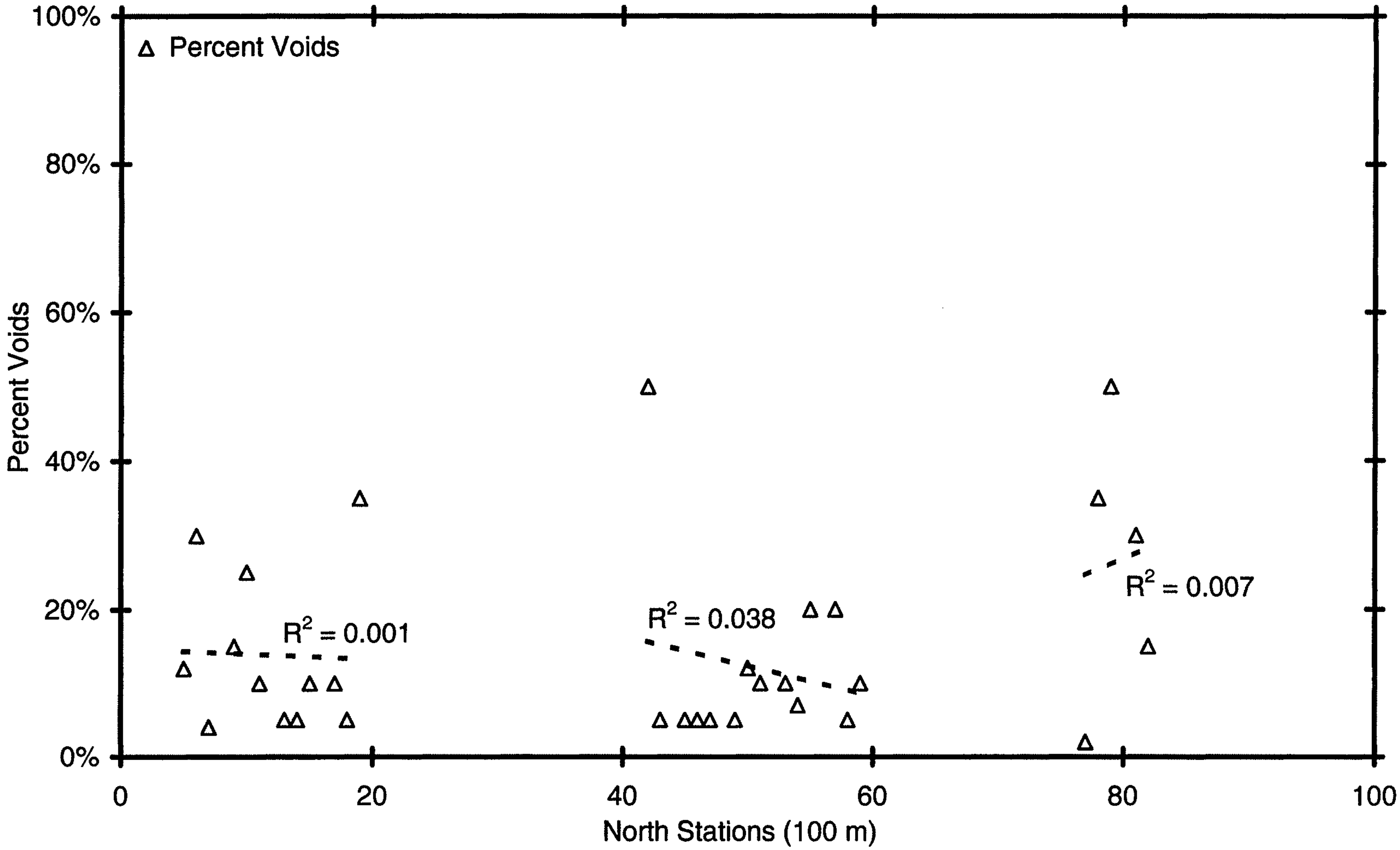

Figure 4.11.c Percent Voids, 2001, Dykes 1 and 2 North

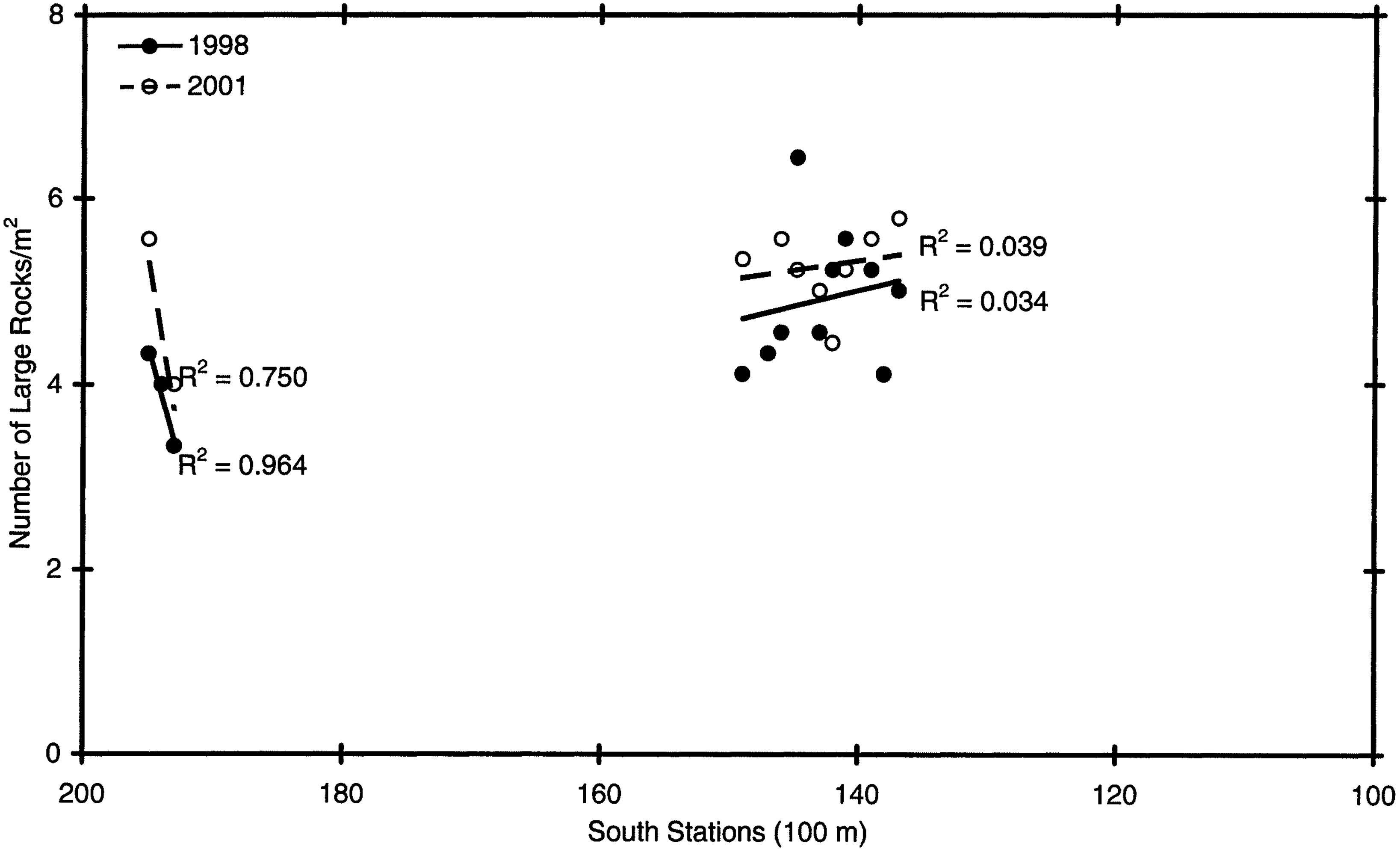

Figure 4.12.a Number of Large Rocks, Dykes 3 and 4 South

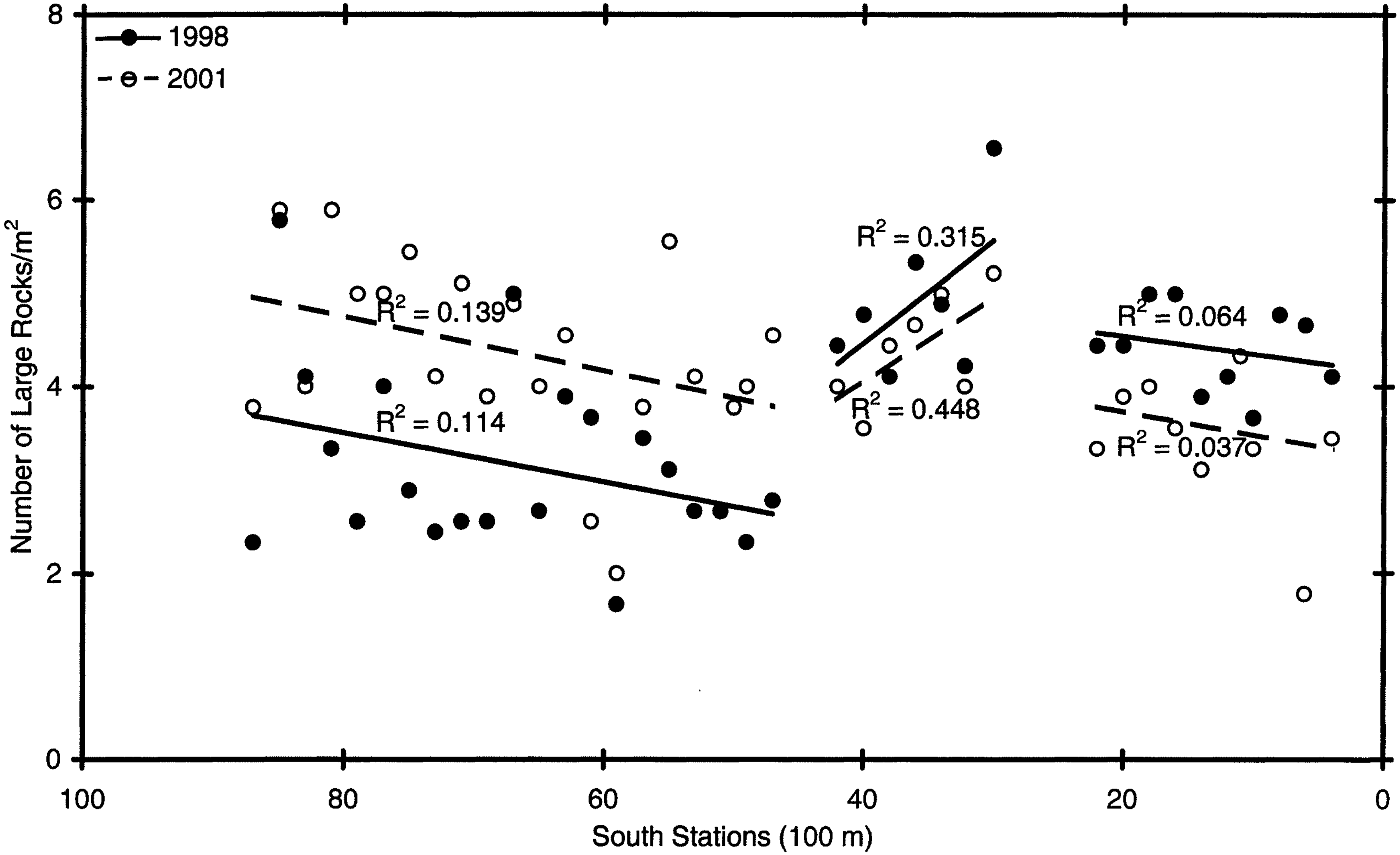

Figure 4.12.b Number of Large Rocks, Dykes 1 and 2 South

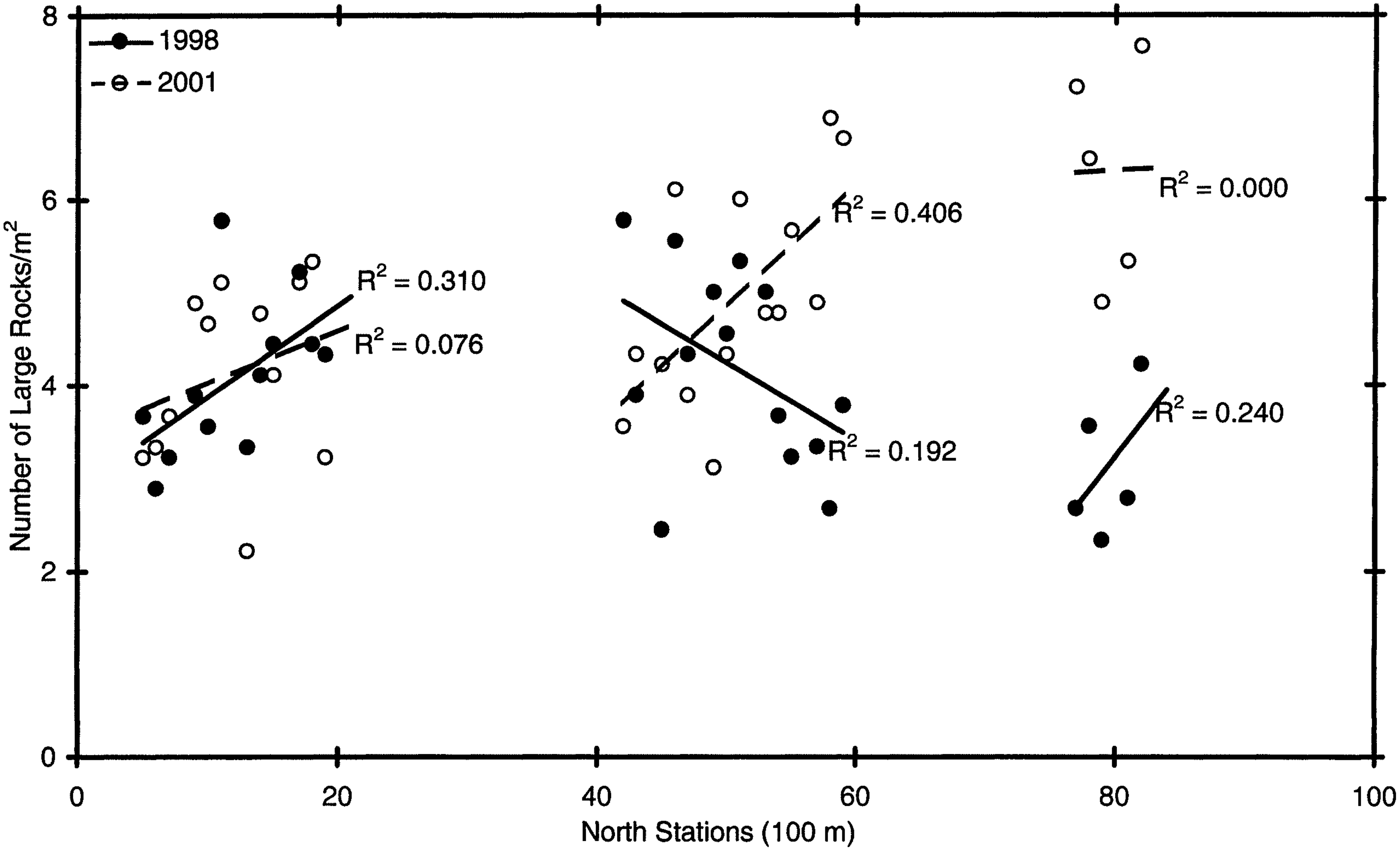

Figure 4.12.c Number of Large Rocks, Dykes 1 and 2 North

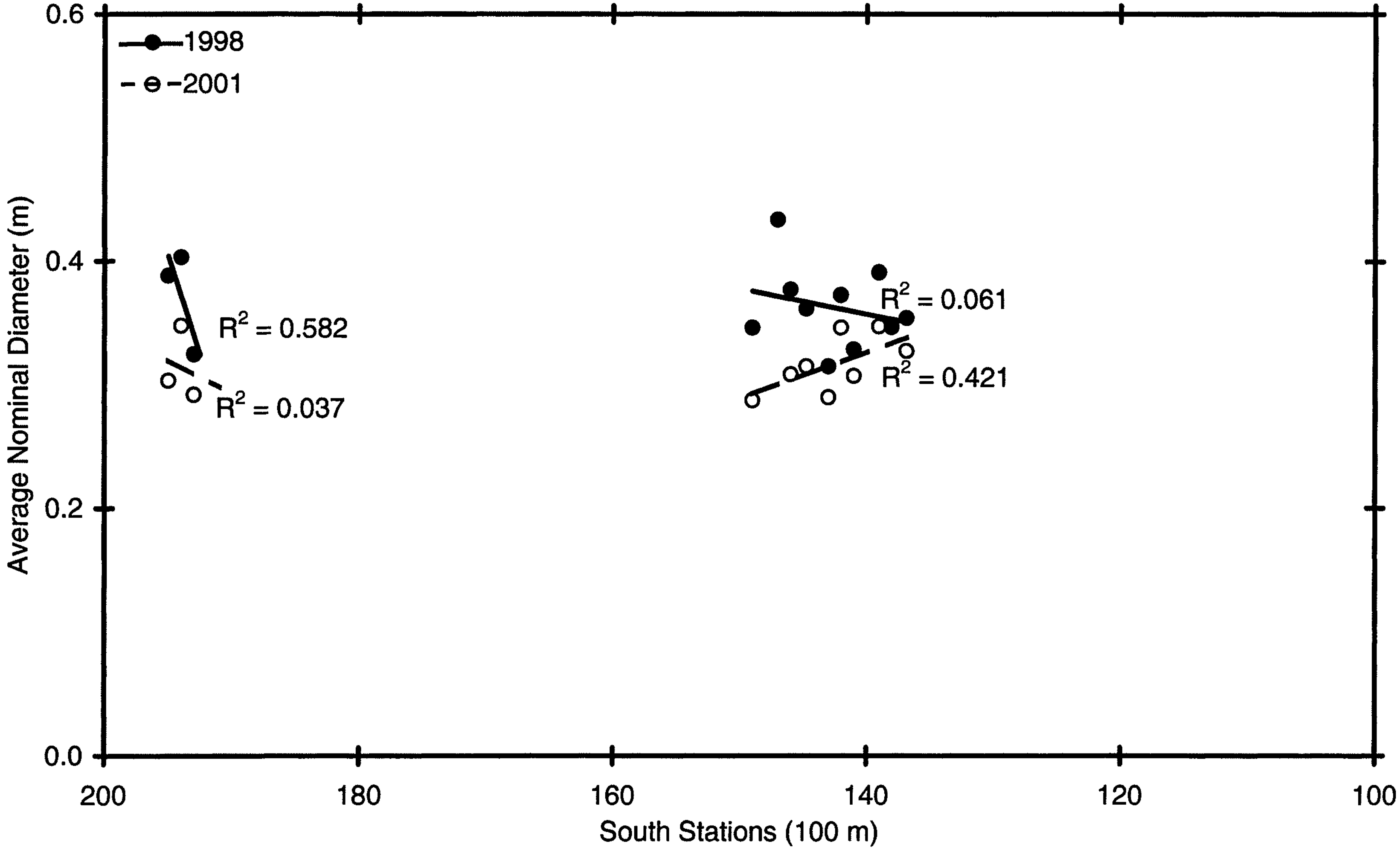

Figure 4.13.a Average Nominal Diameter, Large Rocks, Dykes 3 and 4 South

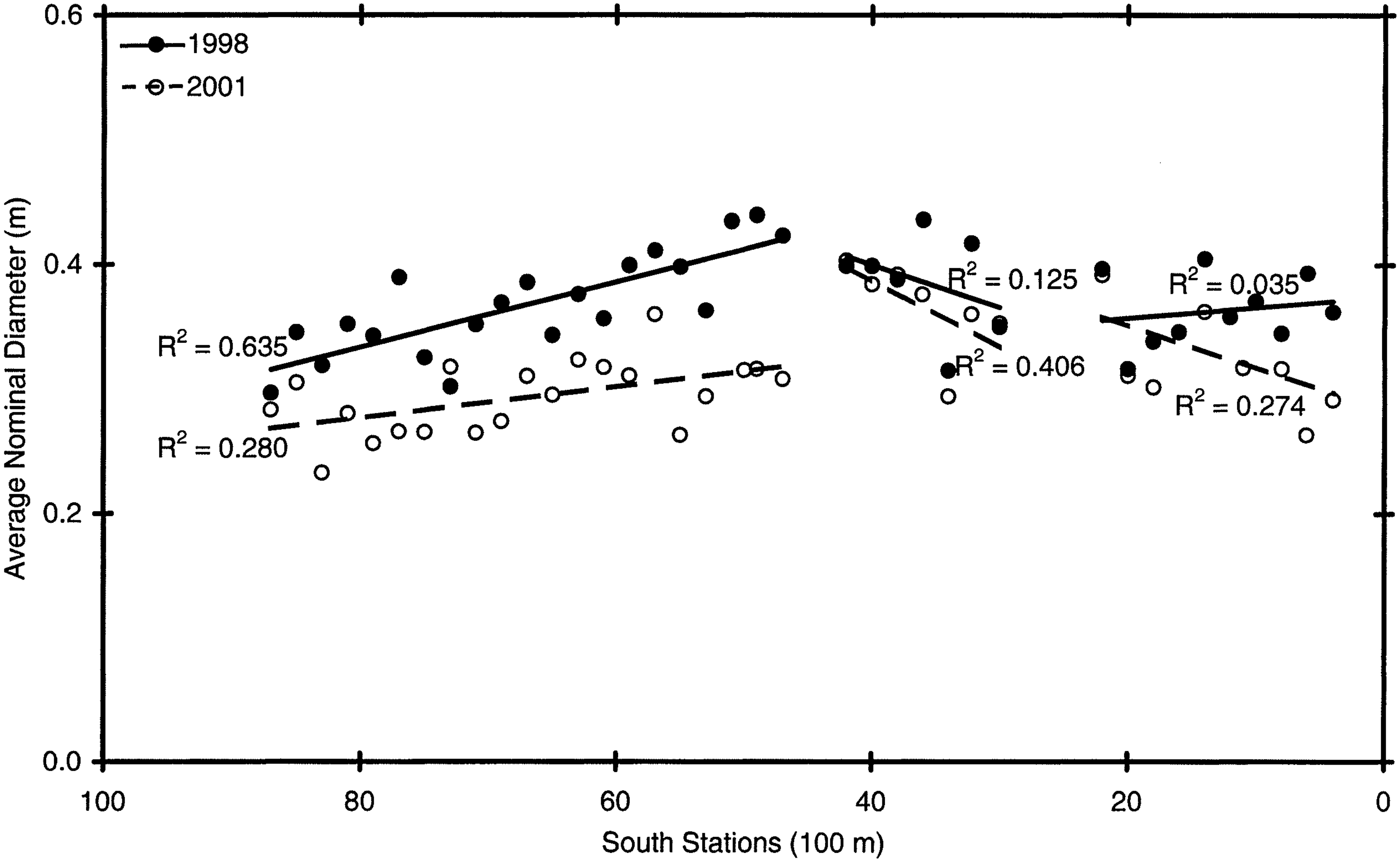

Figure 4.13.b Average Nominal Diameter, Large Rocks, Dykes 1 and 2 South

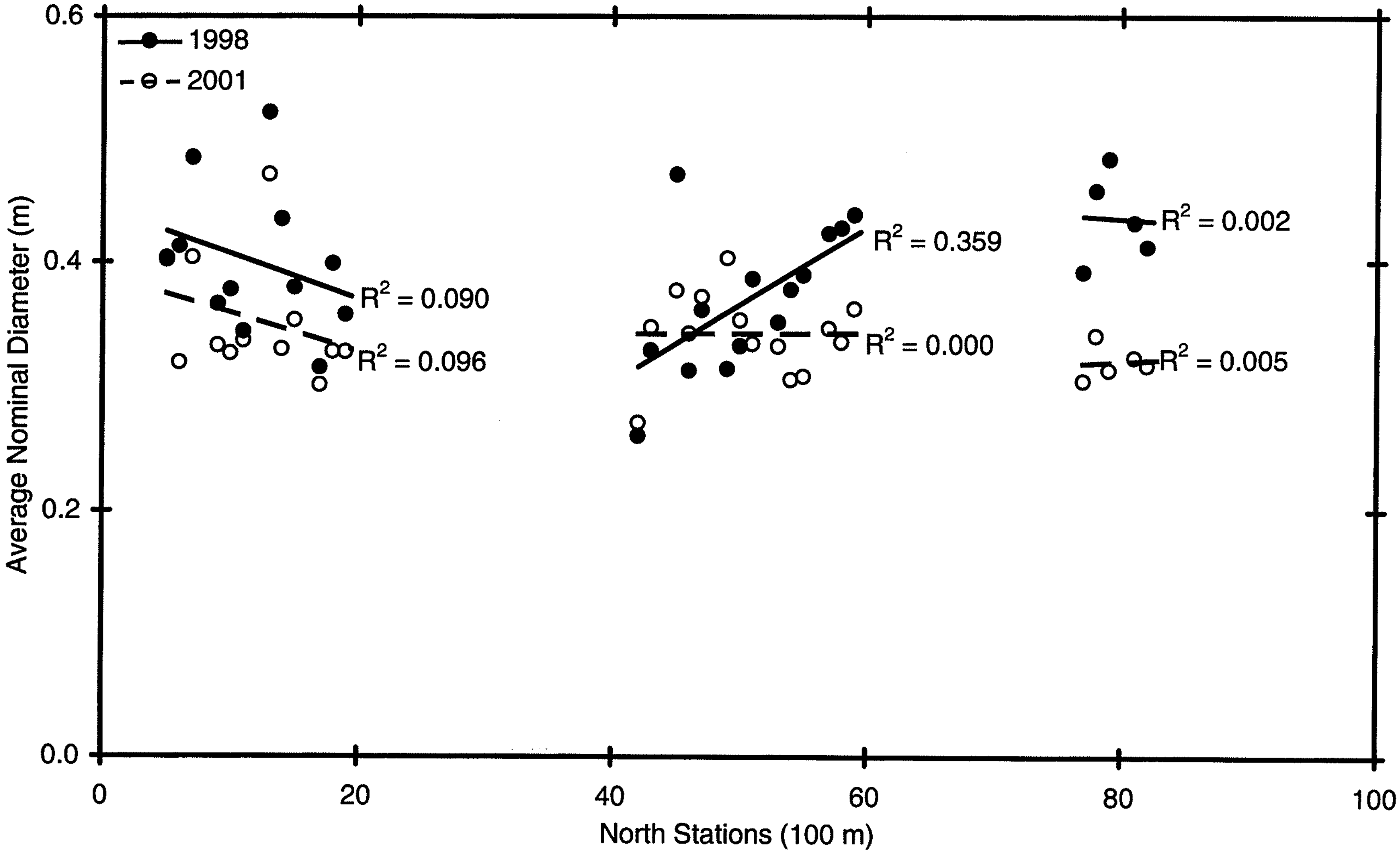

Figure 4.13.c Average Nominal Diameter, Large Rocks, Dykes 1 and 2 North

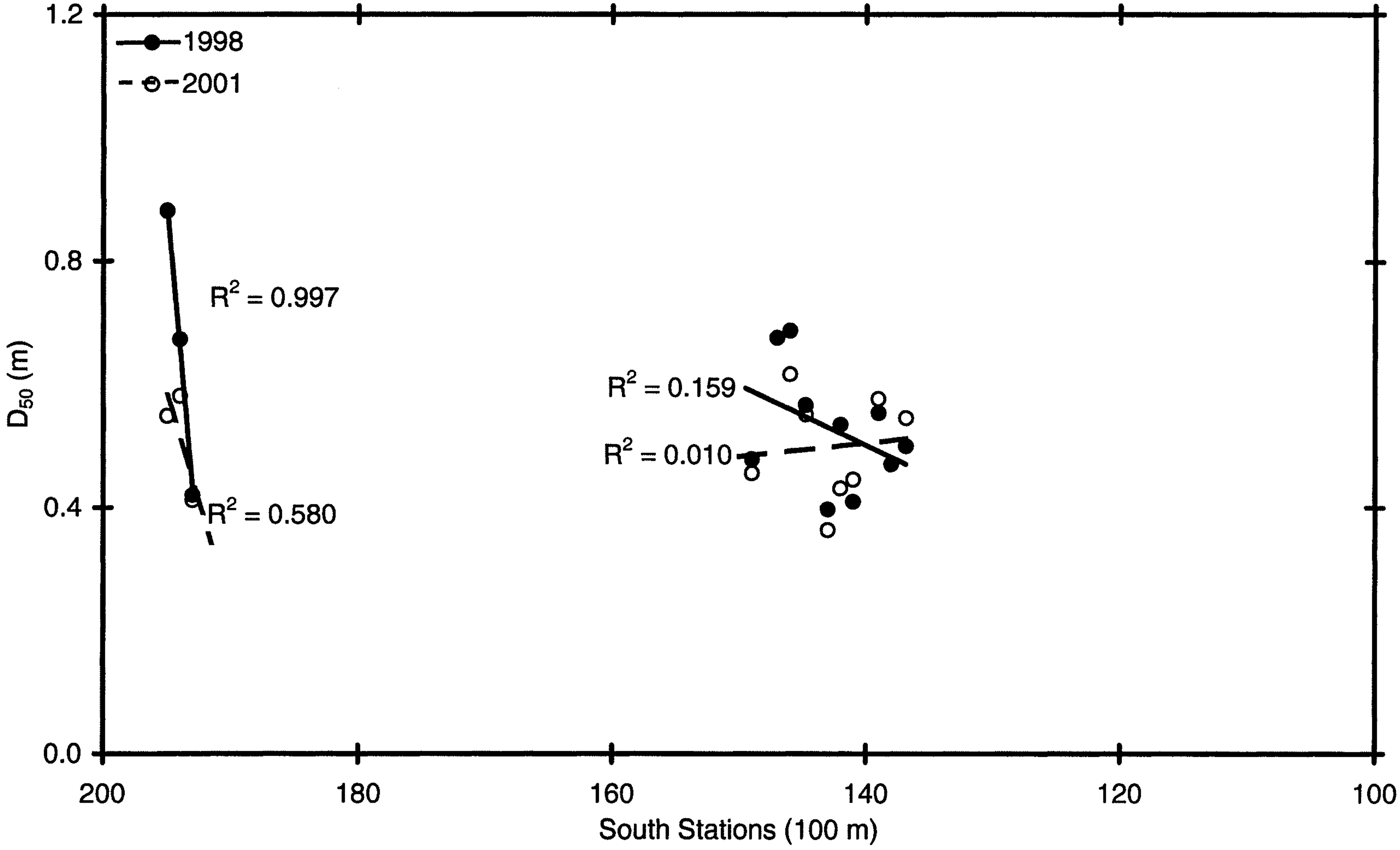

Figure 4.14.a D_{50} Found by Size-Mass Grading of the Intermediate Dimension, Large Rocks, Dykes 3 and 4 South

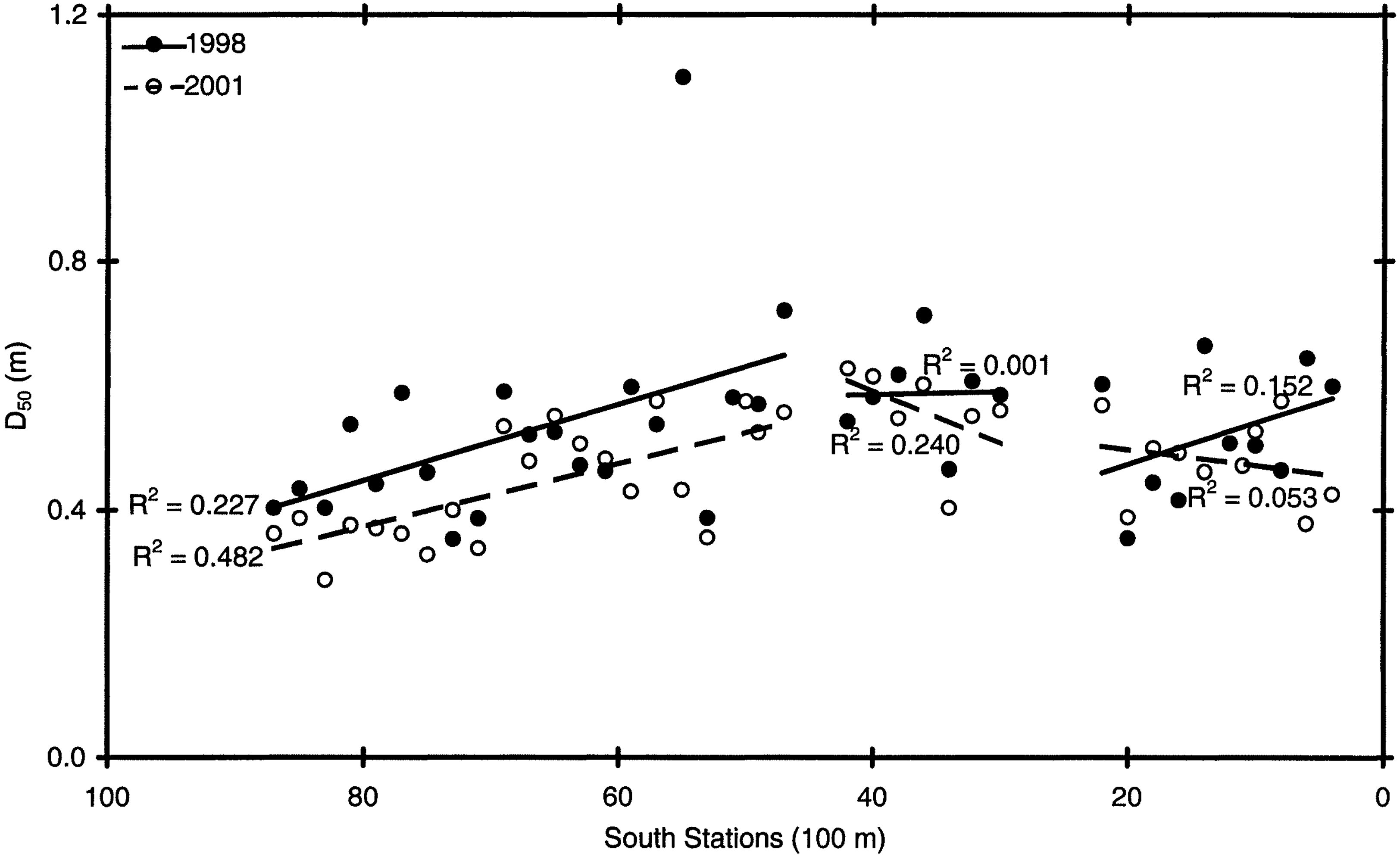

Figure 4.14.b D_{50} Found by Size-Mass Grading of the Intermediate Dimension, Large Rocks, Dykes 1 and 2 South

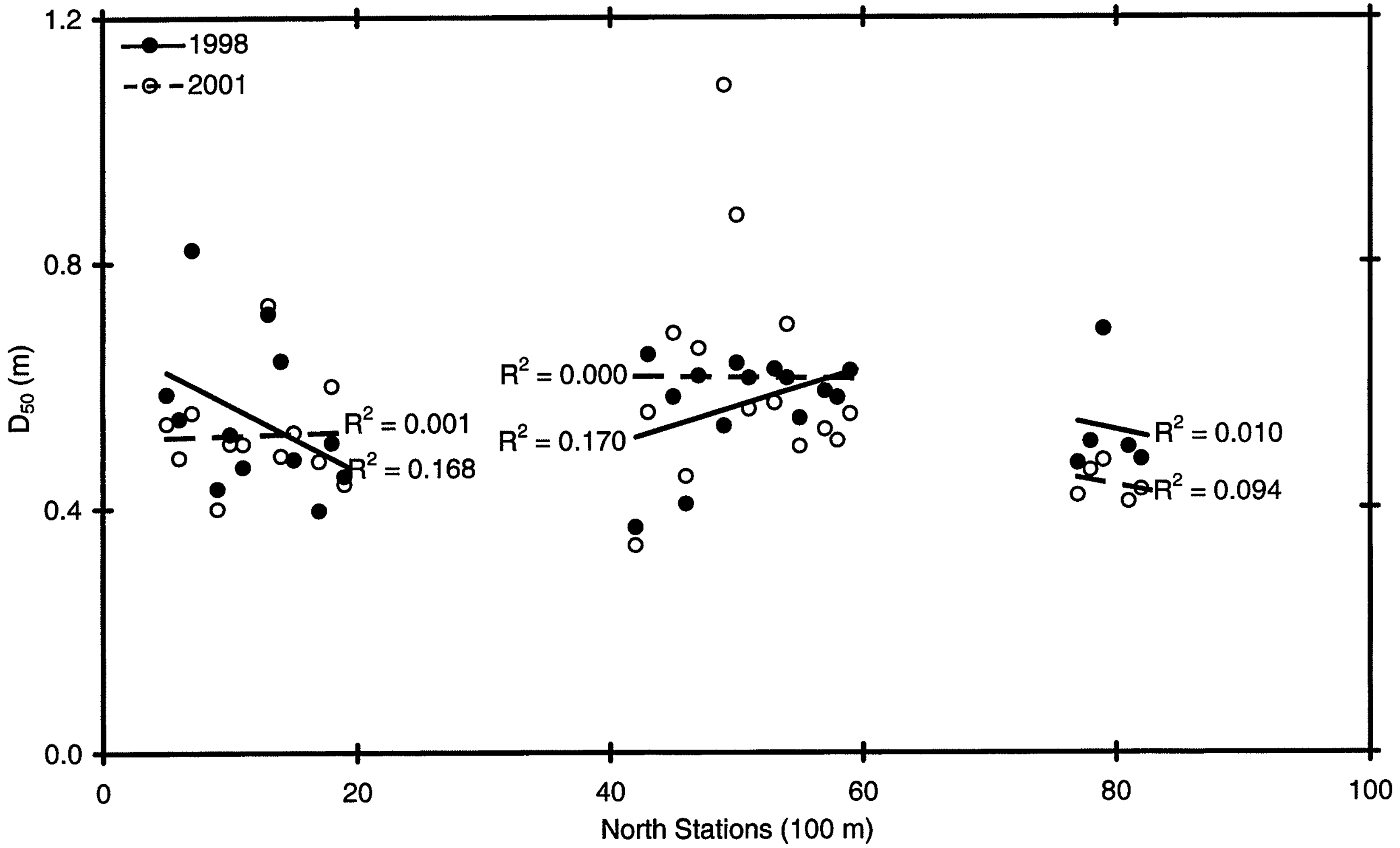

Figure 4.14.c D_{50} Found by Size-Mass Grading of the Intermediate Dimension, Large Rocks, Dykes 1 and 2 North

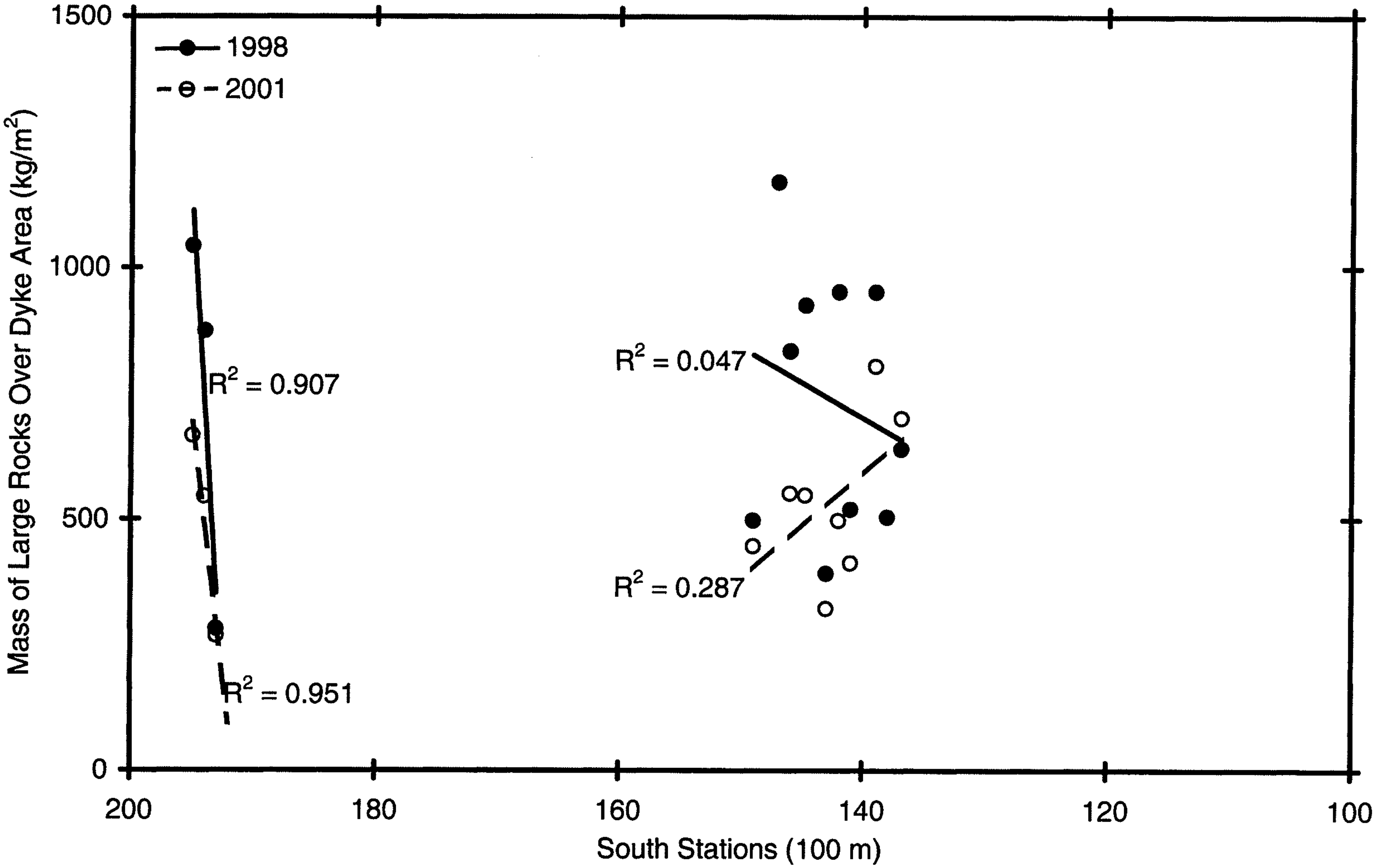

Figure 4.15.a Mass, Large Rocks, Dykes 3 and 4 South

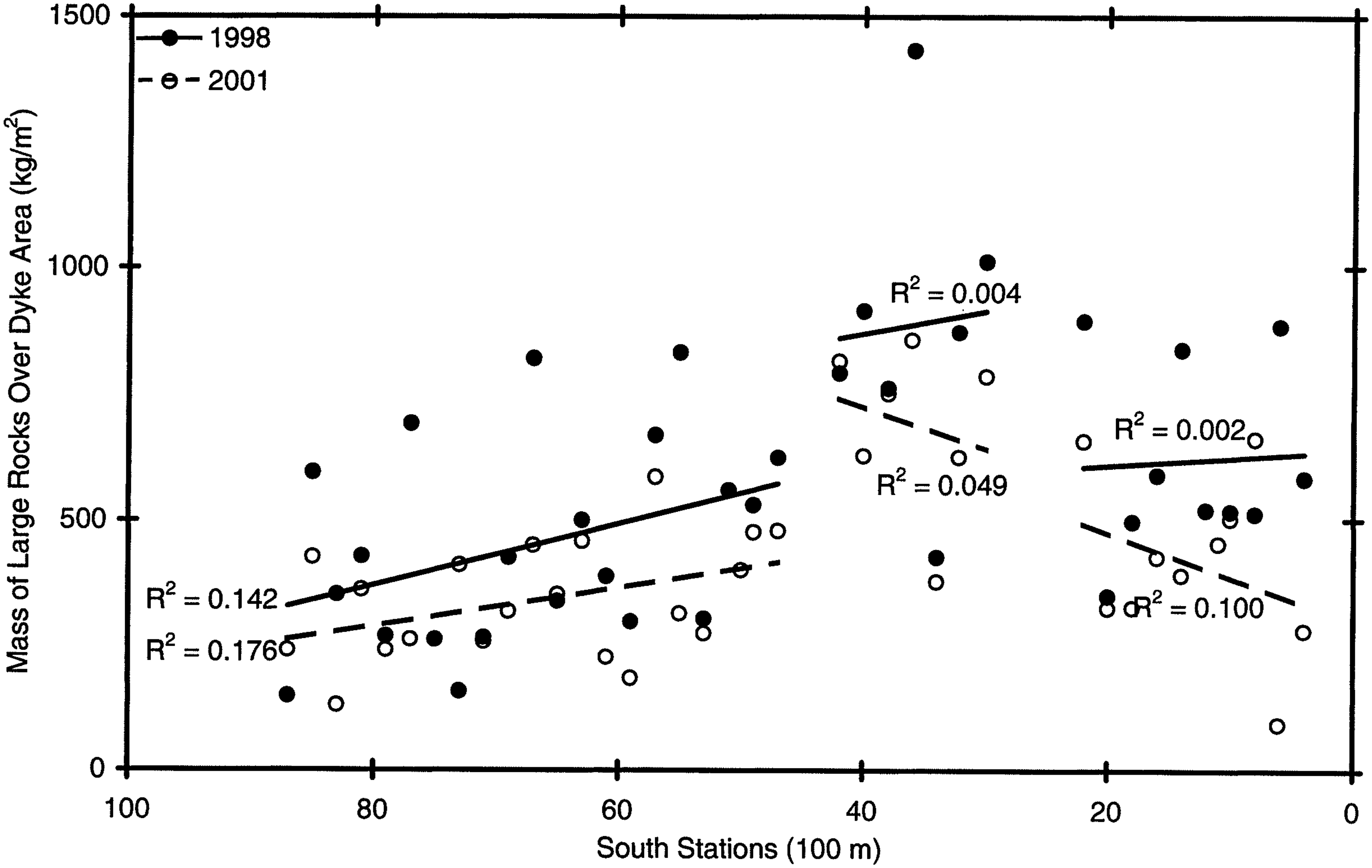

Figure 4.15.b Mass, Large Rocks, Dykes 1 and 2 South

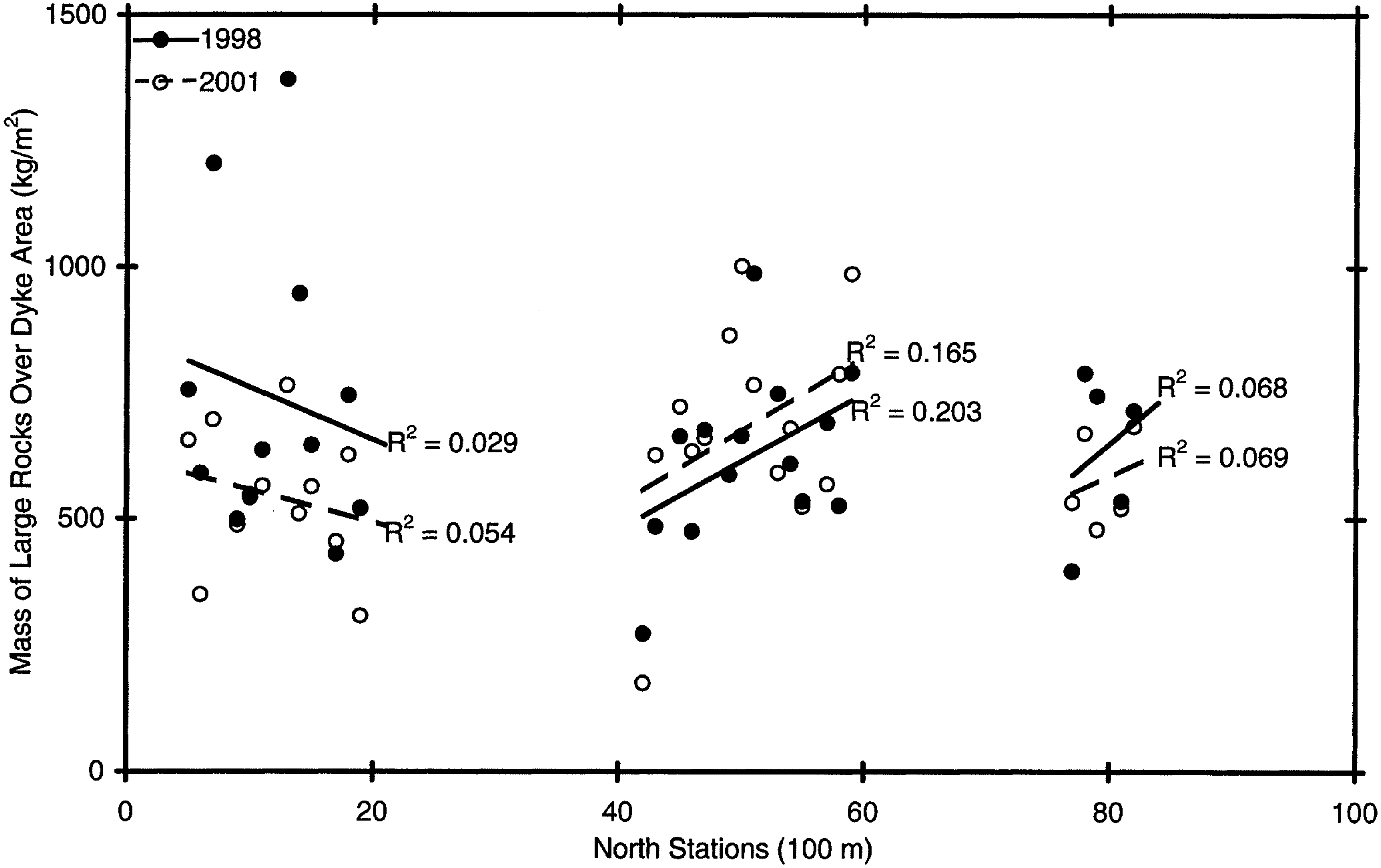

Figure 4.15.c Mass, Large Rocks, Dykes 1 and 2 North

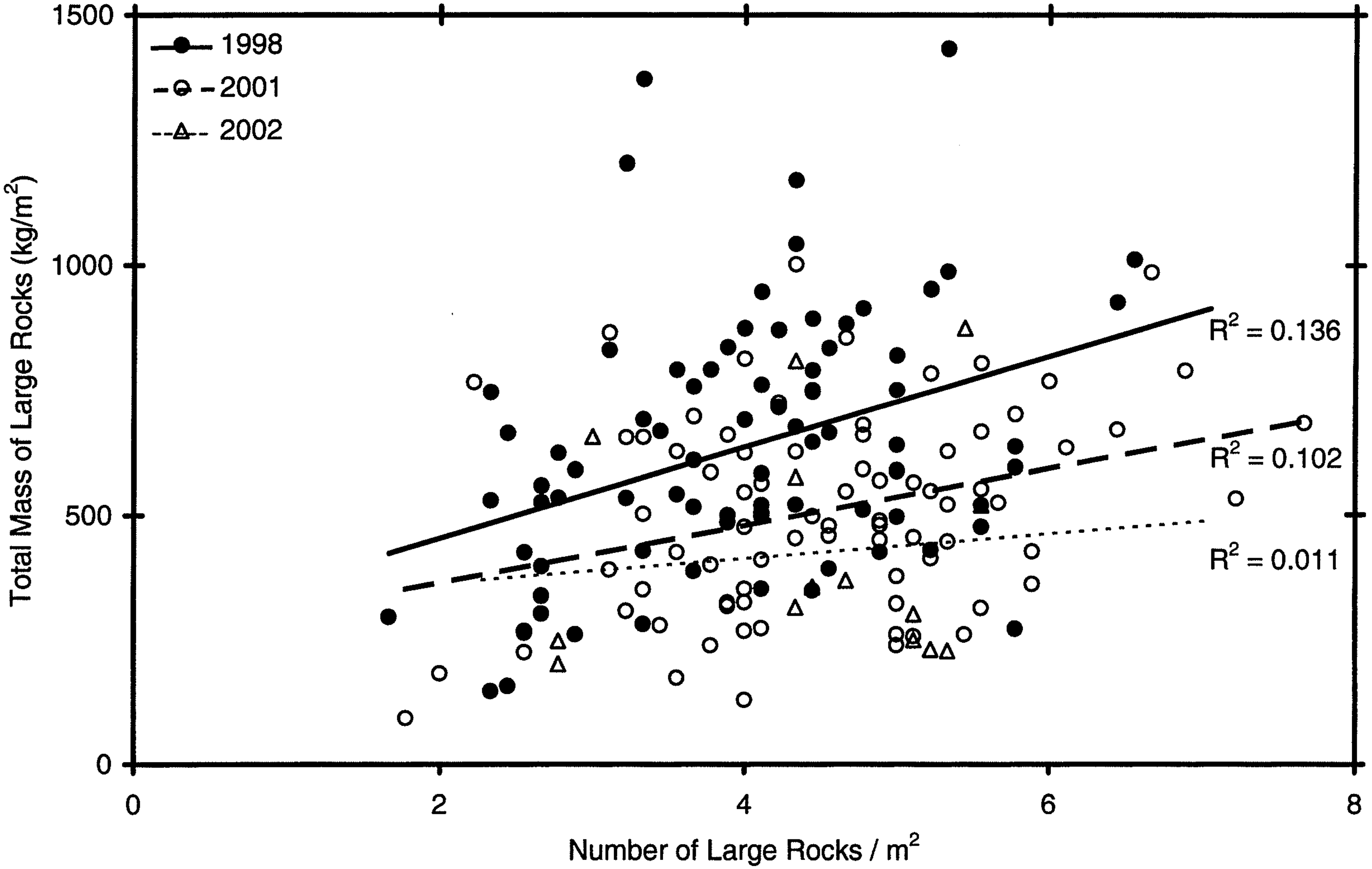

Figure 4.16 Number of Large Rocks versus Total Mass of Large Rocks

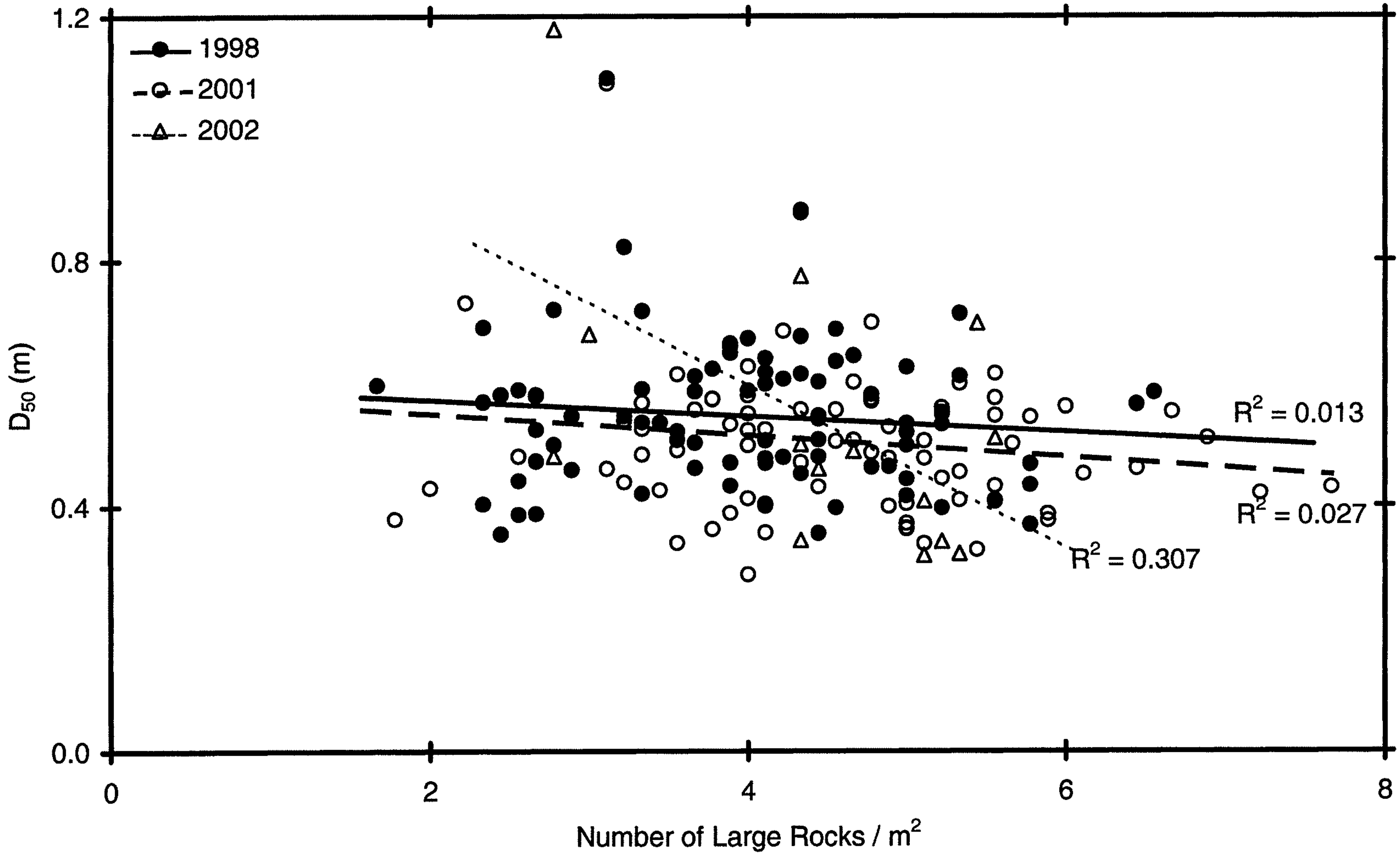

Figure 4.17 D_{50} versus the Number of Large Rocks

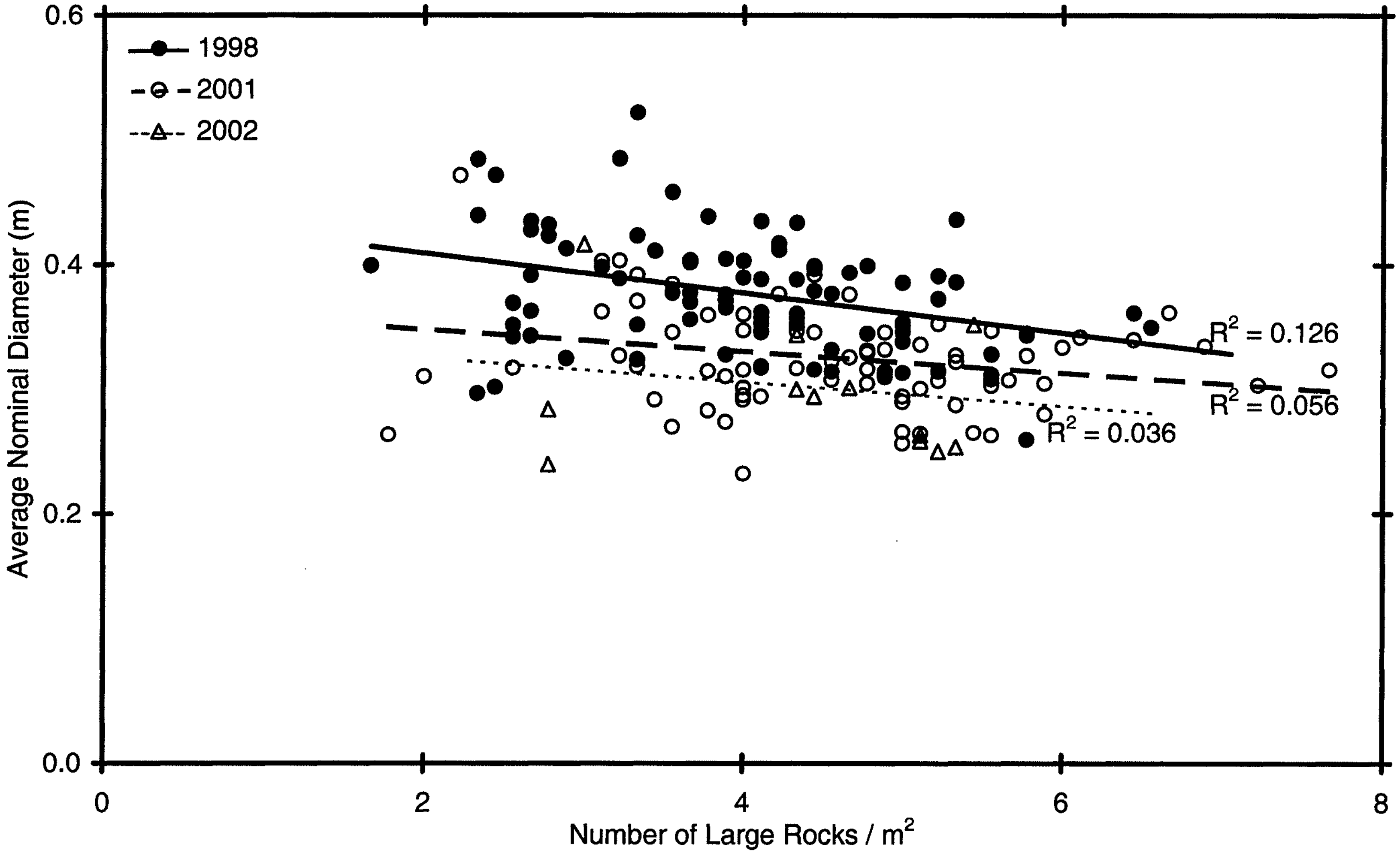

Figure 4.18 Number of Large Rocks versus Average Nominal Diameter

Figure 4.19 Photograph of Beaching Dyke 2 North 78+90

Chapter 5: Report on Laboratory Testing

5.1. Introduction

As a result of changes in forebay level and weather, the riprap along the dykes being studied undergoes cycles of wetting and drying, and cycles of freezing and thawing on a regular basis.

The wetting-drying cycles experienced by an individual piece of riprap are mainly influenced by the forebay level, precipitation and wind events. The forebay level may be raised or lowered depending on the expected need for electrical generation, it tends to be highest in the fall and lowest in the spring. The effects of rainfall are self-evident, but vary with rainfall during the year. Wind events can increase the wave run-up on the dyke face and wet otherwise dry rocks.

The freezing-thawing cycles are influenced mainly by the climate of the area. In the fall, the temperature drops below freezing and rises again in the spring. During these seasons, the temperature may fluctuate multiple times causing many freezing-thawing cycles in the riprap. Another aspect to these cycles is the fact that the forebay level is at its highest level in the fall, meaning that a large portion of the rocks on the dyke becomes wet and undergoes freezing-thawing cycles in that condition.

In order to determine the effects of these cycles on the riprap material being studied, ASTM tests for wetting-drying cycles and freezing-thawing cycles, and the Iowa Pore Index test were performed on samples of the riprap. A petrographic description of each sample was taken, as well as bulk specific gravity and absorption tests to determine if there are any useful correlations between these and the durability of the riprap.

Samples of the riprap were taken directly from the dykes for laboratory testing. Due to time and laboratory constraints, the sample size was kept relatively small. A total of 17 samples were tested. The samples were taken at random locations across the dyke system and were chosen to include a representative number of each visible types of rock on the dykes.

The following sections contain a summary of each test performed on the riprap samples and a summary of the methods used to prepare the specimens. Samples were tested in two sets and labelled by their set and number. The first set of samples were tested in spring 2002 and the second set in fall 2002.

The sizes of the samples were limited by what could be removed from the dyke face without changing the integrity of the dyke and what could be removed by hand. As a result, the samples removed were all under 60 kg in size. Where the riprap sample size was not large enough or where the riprap cracked too much during cutting and there was not enough sample to conduct both freezing-thawing and wetting-drying tests, the wetting-drying test was not conducted. This may have selectively deleted the lowest quality rocks from the test series. The number of samples was limited by available budget for testing and the number that could be tested in freezing-thawing during the schedule.

5.2. Riprap and Sample Descriptions

Before the laboratory work was started, a geologist for the owner of the site examined each sample and provided a description. These descriptions are listed in Table 5.1. They can be summarized as follows. The riprap samples are mainly argillaceous (clayey or shaly) limestone. This rock is generally aphanitic (no discernible crystalline structure). While most are massive, some are slabby and may have visible bedding planes. Some of the rocks are clastic, with off-white clasts imbedded within a soft yellow background matrix. The limestone generally varies in colour from white to tan (or yellow), but some of the rocks have reddish or brownish bedding planes that are likely iron rich. The riprap was produced in a number of quarries on the owner's property surrounding the dyke system at the site being studied. Two samples of granite were tested as a benchmark for the limestone samples.

5.3. Bulk Specific Gravity and Absorption

5.3.1 Introduction and Definition

Bulk specific gravity and absorption are two properties used to compare rocks. These two properties are found using the same testing procedure but with separate calculations. These properties are found using standard ASTM test methods.

Bulk specific gravity for rock samples is determined using a different approach than specific gravity for soils. Unlike soils, rocks contain voids that may not be permeable and it is difficult to determine how much of the rock is void space. Bulk specific gravity includes both the permeable and impermeable voids and can be used to determine the mass or weight of a rock when the volume is known. This is very different from specific gravity (of soils), which does not include the voids.

Bulk specific gravity is defined as the "ratio of: (1) the weight in air of a given volume of a permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to (2) the weight in air of an equal volume of distilled water at a stated temperature." (ASTM 1997). This ratio is dimensionless and mass can be substituted for weight when calculating the result. A similar definition and calculation is called "bulk relative density" by the Canadian Standards Association (CSA 2000). In this research, the term "bulk specific gravity" is used.

Absorption is the mass of water which infiltrates permeable rock voids, expressed as a percentage of the dry mass of the rock. It is also a dimensionless ratio, for which mass and weight can be substituted when calculating the result.

5.3.2 Summary of ASTM C 127 – 88, Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate (ASTM 1988.)

A test specimen is created for each sample of riprap from the remaining cuttings for other tests. Each specimen is dry sieved to remove pieces smaller than 4.75 mm, then washed to remove all dust.

Once clean, each specimen is oven dried and the mass determined (A). The specimen is then submerged in water for approximately 24 hours, surface dried with absorbent cloth and mass determined again (B). The specimen is then submerged in water and the mass is once more determined (C).

The bulk specific gravity for each specimen is calculated using the following equation:

$$\text{Bulk specific gravity} = \frac{(A)}{(B - C)} \qquad [5.1]$$

Where:

A = mass of oven dry specimen in air,

B = mass of saturated surface dried specimen in air, and

C = mass of saturated specimen in water.

Where two specimens of the same sample rock were measured, the average is found by the following equation:

$$\text{Average Bulk Specific Gravity} = \frac{1}{\frac{P_1}{100 \times G_1} + \frac{P_2}{100 \times G_2}} \qquad [5.2]$$

Where:

P_1, P_2 = percent of specimen mass from the total of both specimen, and

G_1, G_2 = bulk specific gravity of specimen.

The absorption is found using the same information as the bulk specific gravity, in the following equation:

$$\text{Absorption (percent)} = \frac{(B - A)}{A} x 100 \qquad [5.3]$$

Where:

A = mass of oven dry specimen in air, and

B = mass of saturated surface dried specimen in air.

Where two specimens of the same sample rock were measured, the average is found by the following equation:

$$\text{Average Absorption (percent)} = \frac{P_1 \text{ x } A_1}{100} + \frac{P_2 \text{ x } A_2}{100} \qquad [5.4]$$

Where:

P_1, P_2 = percent of specimen mass from the total of both samples, and

A_1, A_2 = absorption of specimen.

5.3.3 Results

The results of bulk specific gravity and absorption in limestone riprap varied considerably since limestone is relatively porous and also variable. These results can be found in Table 5.2. The bulk specific gravity varied from 2.28 to 2.81, with an average of 2.63. The absorption varied from 0.2% to 6.4%, with an average of 2.3%.

Some of the variability seems to be related to the rock type. The four rock specimens described as clastic in Table 5.1 (R4, R5, R8, and R17) have significantly lower bulk specific gravities (2.29 to 2.43) and higher absorption (4.3% to 6.4%) than the rest of the specimens. The bulk specific gravity for rest of the limestone specimens is higher (2.59 to 2.81) and absorption is lower (0.4% to 2.7%). The specific gravity for the granite specimens was 2.66 and 2.74, which is in the same range as the limestone, while the absorption was considerably lower than the limestone at 0.1% and 0.2%.

5.4. Preparation of Rock Slabs for Durability Testing

5.4.1 Summary of ASTM D 5121 – 90, Standard Practice for Preparation of Rock Slabs for Durability Testing (ASTM 1990)

This ASTM Standard describes the method used to cut the rock for the wetting-drying tests and freezing-thawing tests. Each rock was clamped and then cut with a rock-saw in a manner to prevent breakage (especially along planes of weakness). After each cut the rock was washed and inspected for breakage. The rocks were cut into blocks as described in the tests below.

5.5. Durability of Rock for Erosion Control Under Wetting and Drying Conditions

5.5.1 Introduction

As mentioned in Section 5.1, the forebay elevation at the site varies daily as well as annually, causing rocks to be wetted and dried regularly. The ASTM test method evaluates the durability of riprap to withstand this wetting and drying.

5.5.2 Summary of ASTM D 5313 – 92, Standard Test Method for Evaluation of Durability of Rock for Erosion Control under Wetting and Drying Conditions (ASTM 1992b)

Each specimen for the test is cored out of the sample rock using a core-drill and cut into a square specimen, approximately 150 mm on each side and 65 mm high. The specimen is labelled and photographed. It is then dried and weighed. The specimen is placed in a container on a thin layer of sand and immersed in water for 12 hours, then drained. The wetting-drying test consists of cycles of drying the specimen in an oven during the day and immersing it in water overnight.

The specimens are visually examined every few days and notes are made of any signs of change. At the end of 80 cycles, the specimen is dried, weighed, photographed, and notes are made of any changes.

To determine the percent loss for each specimen, the following equation is used.

$$\text{Percent loss} = \frac{(\text{original - final specimen weight})}{(\text{original specimen weight})} \times 100 \qquad [5.5]$$

5.5.3 Results

Table 5.3 shows that the results of the wetting-drying test are practically negligible. The loss of mass ranges from 0 to 0.03% and is barely within the limit of the significant figures that can be measured in the laboratory.

5.6. Durability of Rock for Erosion Control Under Freezing and Thawing Conditions

5.6.1 Introduction

It is believed that the major portion of degradation of riprap at the site being studied is due to freezing-thawing conditions in fall and spring. In the fall, the reservoir is typically at its highest level, saturating most of the rocks on the dyke faces. This is coupled with typical fall winds that create waves, and saturate even more riprap during the period of alternating freezing and thawing before the reservoir freezes for the winter. In the spring, riprap undergoes more freezing-thawing cycles, again under saturated conditions as the ice and snow melts off the dykes.

The ASTM standard freezing-thawing test method requires an initial saturation of the riprap specimen and the specimen is tested sitting on a saturated carpet. The specimen may not remain fully saturated as it may drain or soak up water from the saturated carpet. To test the riprap specimens in a more fully saturated environment, the specimens were covered with cheesecloth and an extension of the standard test was conducted with additional freezing-thawing cycles.

5.6.2 Summary of ASTM D 5312 – 92, Standard Test Method for Evaluation of Durability of Rock for Erosion Control under Freezing and Thawing Conditions (ASTM 1992a)

Each specimen for the test is cored out of the sample rock and cut into a square specimen approximately 130 mm on each side and 62 mm high. The specimen is labelled and photographed, then dried and weighed. The specimen is placed in a container on a layer of carpet and immersed in an alcohol-water solution for 12 hours, then drained. The alcohol-water solution is kept level with the top of the carpet throughout the test. The freezing-thawing test consists of cycles of freezing the specimen for 12 hours at -18 °C and thawing it for 12 hours at 32 °C in a freezing-thawing chamber that controls the temperature and timing.

The specimens are examined visually every few days and notes of any signs of change to the appearance of the surface are made. At the end of 30 cycles (the number of cycles is dictated by the geographic location of the study site), the specimens are dried, weighed, photographed, and notes are made of any changes.

To determine the percent loss for each specimen, the following equation is used:

$$\text{Percent loss} = \frac{\text{(original - final specimen weight)}}{\text{(original specimen weight)}} \times 100 \qquad [5.6]$$

5.6.3 Saturated Test Method

Once the ASTM test was complete, many of the specimens appeared dry on top, even though the base was kept wet. This does not represent the worst case in the field. As the water level in the forebay is relatively high in the fall, most of the rocks on the dyke face are either under water or are subjected to wetting and drying wave action. It was also noted that the amount of loss of mass was significantly lower than expected, based on anecdotal information of the performance of the riprap at the site being studied for this research. It was decided to extend the number of cycles in the tests and place cheesecloth connected to the water supply over the specimens to maintain the moisture in the samples. The test was continued another 81 cycles, to try to reproduce the levels of deterioration seen at the study site. The same calculation was performed for the percent loss at the end of the test.

5.6.4 Results

The standard ASTM method and the extended method described in the previous section produced broadly similar results, except that the extended portion of the test produced results of a greater magnitude. These results are listed in Table 5.4. The ASTM results vary from 0 to 10.8% loss of the mass of the rock, while the results from the extended portion of the tests vary from 0 to 97.8% loss.

Again there is a relation to rock type. All of the specimens with the red or brown bedding layers performed poorly, while all of the clastic specimens performed well. Most of the off-white specimens performed well, but two specimens performed worse than the rest. The specimens with red bedding layers lost 2.5% to 4.0% of their mass in the ASTM portion of the test and up to 8.8% by the end of the freezing-thawing test. The specimen with brown bedding layers was not far behind with 1.5% loss in the ASTM portion and 4.8% loss by the end of test. Of the off-white specimens that performed poorly, one lost 10.8% of its mass in the ASTM portion and 12% by the end of the test. The other off-white specimen that performed poorly lost 0.3% of its mass in the ASTM portion of the test, then shattered in the extended portion of the test losing a total of 97.8% of it's original mass. The rest of the riprap specimens varied little, losing up to 0.6% in the ASTM portion and up to 1.3% of their mass in the extended portion of the test. The granite specimen lost no detectable mass in either portion of the test.

5.7. Iowa Pore Index Test (IDOT 1980)

5.7.1 Introduction

The Department of Transportation in Iowa developed this test, when they found that the standard tests of aggregate (for use in concrete) durability were not accurately predicting the susceptibility of the aggregate to freezing-thawing failure. This test measures how much water the permeable rock voids can absorb under pressure, during a defined test duration.

The Iowa Department of Transportation found that results of this test correlate directly with “D-cracking” (cracking due to freezing and thawing) of concrete that included the aggregate tested. Where the Iowa pore index number is greater than 27, concrete using that aggregate was found to be susceptible to D-cracking. Where the results were 27 or less, no association with D-cracking was found, and the aggregate was deemed acceptable for use. (See Appendix A for further information.)

5.7.2 Procedure

To perform this test, an Iowa Pore Index Container was designed using a metal container called a ‘press-ur-meter’. For the Pore Index test, the equipment in the lid of the ‘press-ur-meter’ was replaced with a 32 millilitre Plexiglas tube, which is marked for 2 millilitre increments.

The rock specimen is crushed or cut to a maximum size of 19 mm (¾ inch) with an average of 12.7 mm by 19 mm (½ inch by ¾ inch). The aggregate is then oven dried, and an amount less than 9000 grams is placed in the Iowa Pore Index Container. The container is filled to the zero mark and air pressure is applied to a level of 240 kPa (35 psi).

The amount of water (in millilitres) taken in by the aggregate is measured at specified intervals for 15 minutes. The amount of water taken in during the first minute is called the primary load, and the amount taken in between the first minute and the fifteenth minute is called the secondary load. The results are extrapolated using mass to a standard specimen size of 9000 grams. The standardised secondary load becomes the Iowa pore index number.

5.7.3 Results

Results from the Iowa Pore Index test are shown in Table 5.5. The Iowa Pore Index number ranged from 0 to 51 ml. Most specimens of the limestone had an Iowa pore index number less than 27 ml. However, all of the specimens with red or brown bedding planes had a pore index number greater than 27 ml. The clastic specimens were well below 27 ml in the range of 6 to 7 ml. The granite specimen had a pore index of 0 ml.

The primary load results are considerably different. Most of the limestone, specimens including the specimens with red bedding planes had primary loads that varied from 19 to 122 ml, while the clastic specimens were significantly higher at 202 and 231 ml. The primary load for the granite specimen was 42 ml.

5.8. Discussion

Most of the tests produced consistent results, although they varied from what was initially expected. Theoretically, limestone with high absorption (therefore larger pore sizes and lower bulk specific gravity) can be expected to perform poorly in freezing and thawing, but this is not shown by these results. The clastic specimens had a relatively high absorption and low bulk specific gravity, but performed very well in the freezing-thawing and Iowa Pore Index tests. Meanwhile the specimens with red and brown bedding layers performed the worst in freezing-thawing tests and Iowa Pore Index tests, even though their specific gravity and absorption did not indicate that they would have larger pores. The bulk specific gravity and absorption results were generally as expected. The limestone bulk specific gravity results were in the general range indicated by "Geology Applied to Engineering" (West 1995) and fell between 2.28 to 2.81. The absorption varied from 0.2% to 6.4%, as expected in rocks with a porous nature, such as limestone.

Figure 5.1 shows an inverse linear correlation between the absorption and the bulk specific gravity, in the limestone samples tested. The clastic limestone specimens have the highest absorption percentages and the lowest specific gravity. As the bulk specific gravity decreases, the absorption increases. This relationship is expected in a porous rock such as limestone, since the number and size of the pores within the rock will affect the bulk specific gravity. The more frequent and the larger the pores, the higher the absorption and the lower the bulk specific gravity. This correlation has an R^2 value of 0.99. This R^2 value is relatively high, indicating a good relationship.

The granite specimens fall outside the limestone association in Figure 5.1. These have very low absorption because they have very few and very small pores. Their bulk specific gravity relates more specifically to the minerals within the granite.

Unexpectedly, all specimens performed well in wetting-drying tests, with negligible results in all rock types. This indicates the wetting and drying at the site studied is probably not by itself the primary process affecting the disintegration of the riprap.

The net result of the freezing-thawing tests was also not expected. About half of the limestone specimens performed very well in freezing-thawing tests, with losses less than 1% of the dry mass, even after the extended freezing-thawing test, yet the field observations describe significant deterioration.

The most obvious assumption is that a high absorption and low bulk specific gravity would relate directly to poor performance in freezing-thawing tests. Figure 5.2 demonstrates this is not accurate. The clastic rock specimens with low bulk specific gravity did well in freezing-thawing tests and the specimens with red or brown layering did poorly, even though their bulk specific gravity is higher and falls within the range of the rest of the limestone specimens. In fact there is no visible relationship between bulk specific gravity and these freezing-thawing testing results.

Figure 5.3, shows no apparent relationship between freezing-thawing test results and percent absorption. The graph and its interpretation are very similar to those for Figure 5.2 The clastic rock specimens have high absorption rates, yet performed well in freezing-thawing tests, while the red and brown layered rock specimens performed poorly, even though their absorption ratios were lower than those of the clastic rocks. Most of the limestone and the granite specimens had even lower absorption percents and performed very well in freezing-thawing tests.

These results are counter-intuitive, as water filled pores in rocks are expected to cause disintegration when the water freezes and expands. We can normally expect these pores to freeze inwards from the outside, trapping water and causing damage, such as cracking within the rock. This means that the pore sizes are not directly related to the ability of the rock to perform well in freezing-thawing conditions.

A possible hypothesis to explain the difference between the results of the freezing-thawing and the wetting-drying tests and the anecdotal information, is that any riprap that would have significant amounts of deterioration in these tests, has already degraded beyond the acceptable size studied in this research. This would mean the riprap remaining, that is, the material that is still available for sampling and testing, provides only long-lasting pieces, which, not surprisingly, do well in durability tests. Alternatively, samples that might have been most susceptible to freezing and thawing became unsuitable for testing during specimen preparation.

When considered in relation to the freezing-thawing test results, the Iowa Pore Index test produced the interesting relationships seen in Figure 5.4. Here, the clastic specimens performed very well in the Iowa Pore Index and very well in freezing-thawing tests, while the red and brown (iron-rich) bedded specimens performed poorly in both. All specimens with an Iowa Pore Index result of 27 or less performed very well in the freezing thawing tests. Meanwhile most specimens with a pore index higher than 27 performed poorly in the ASTM portion of the freezing-thawing test and all performed poorly in the extended test. This number, 27, is the same number determined by the Iowa Department of Transportation for sensitivity to D-cracking in concrete pavements.

As a confirmation of the Iowa Pore Index test results, Figure 5.5 shows there is a relatively good relationship between the percent absorption from the bulk specific gravity tests and the total of the standardised primary load and Iowa Pore Index. The correlation produced an R^2 of 0.95. It must be remembered that the Iowa Pore Index test is conducted under pressure, while the absorption is not, so the results will not be exactly the same. Nevertheless, the relationship in Figure 5.5 confirms the general quality of the testing program.

When the freezing-thawing tests were continued beyond the ASTM standard number of cycles with a cheesecloth cover over the specimens, the rocks performed in broadly the same manner as in the ASTM portion of the test. The results seen in Figure 5.4, indicate that the specimens with a Iowa Pore Index number greater than 27 continued to disintegrate and lose mass, while most of the rest of the limestone still did not lose any substantial mass, even though the tests were continued another 81 cycles.

It is significant to note that the Iowa Pore Index test related well to the extended freezing-thawing test. Those specimens with an Iowa Pore Index number at or below 27 had total freezing-thawing results of less than 1.5% loss, while those with Iowa Pore Index numbers greater than 27 experienced 4.5% or more loss. It is important to note however that one of the samples performed poorly in both the Iowa Pore Index the extended freezing-thawing test, but performed well in the ASTM portion of the freezing-thawing test.

The Iowa Pore Index Test has a major advantage that it can be performed significantly more quickly than freezing-thawing tests (approximately 30 minutes as opposed to a minimum of 30 days for freezing-thawing cycles). The Iowa Pore Index test provides perhaps the best indicator from this series of tests that a particular rock material is subject to deterioration.

5.9. Concluding Remarks

In contrast with field observations and anecdotal information that the riprap has deteriorated significantly, the test results generally show relatively small tendency to deterioration.

This is especially true in the wetting-drying and freezing-thawing tests, which were expected to show significant deterioration of the limestone. In general, the limestone did better than expected in all tests, and in many cases performed similarly to the granite samples.

Although unexpected, these results point towards some of the relationships related to the degradation of the riprap. The wetting and drying of the riprap has little effect on the degradation, while the freezing and thawing does. Since most of the riprap on the dyke system is exposed to wetting at freeze-up, this becomes a significant parameter in the riprap analysis.

The Iowa Pore Index Test clearly showed a threshold above which deterioration could be quite rapid. It is especially important to note that this test predicted freezing-thawing deterioration in a specimen that did not deteriorate significantly in the ASTM freezing-thawing test, but experienced significant deterioration in the extended test. Considering its ability to predict freezing-thawing deterioration and how quickly it can be performed, the Iowa Pore Index test may become very important.

At this time, there is no method of physically testing the hypothesis that the less durable riprap has already deteriorated (either in the field or during specimen preparation), since the quarries are now closed and there is no access to the original riprap. Further study into the properties of the original riprap, if that were possible, would provide more details to relate the quality of the original rock to that remaining. These results, although unexpected, provide valuable insights into the nature of the degradation processes.

Table 5.1 Rock Sample Descriptions

Rock Number	Rock Type Symbol	Test Sample Number	Description
R1	▲	S-1	Tan, aphanitic, bedded at 2 cm., marker layers off-white to tan.
R2	■	S-2	Tan, aphanitic, layers are marked by iron-rich (rust red) beds, also swirled.
R3	■	S-3	Tan, aphanitic, light brown irregular layering, swirled.
R4	●	S-4	Aphanitic, off-white clasts, matrix is soft yellow in colour.
R5	●	S-5	Aphanitic, off-white clasts, matrix is soft yellow in colour (like Sample 4).
R6	▲	S-6	Light tan to grey, aphanitic, layers.
R7	▲	S-7	Off-white, aphanitic, annealed vertical joint.
R8	●	S-8	Aphanitic, off-white clasts, matrix is soft yellow in colour (Like Sample 4 & 5).
R9	■	S-9	Tan, aphanitic, layers are marked by iron-rich (rust red) beds, also swirled (like Sample 2).
R10	■	S-10	Tan, aphanitic, layers are marked by iron-rich (rust red) beds, also swirled (like Samples 2 & 9).
R11	K	S-11	Granodiorite (Ponton) – biotite is foliated.
R12	K	BR01	Granitic (Whiteshell).
R13	▲	1	Tan, aphanitic, partially porous.
R14	▲	2	Light grey top, tan bottom, aphanitic broken along fractures.
R15	▲	3	Off-white, aphanitic, healed fractures.
R16	▲	4	Off-white, aphanitic.
R17	●	5	Aphanitic clasts, clasts and matrix are soft yellow in colour.
R18	▲	6	Off-white, aphanitic. (Same as 4).
R19	▲	7	Off-white, aphanitic, healed fractures. (Same as 3, fractures are more open.)

Table 5.2 Bulk Specific Gravity and Absorption

Rock Number	Test Sample Number	Mass Oven Dry (g)	Mass Surface Saturated Dry (g)	Mass in Water (g)	Bulk Specific Gravity	Absorp-tion
R1	S-1	902.4 825.0	909.1 830.7	585.4 537.1	2.80	0.7%
R2	S-2	699.7 2090.3	718.4 2122.8	448.8 1345.0	2.66	1.8%
R3	S-3	3299.2 2144.6	3340.6 2180.9	2122.1 1380.6	2.70	1.4%
R4	S-4	2635.3 2803.8	2719.0 2968.5	1380.6 1766.4	2.41	4.6%
R5	S-5	988.6 1412.7	1043.7 1512.4	618.3 882.0	2.27	6.4%
R6	S-6	2629.2 1576.1	2640.7 1581.6	1703.1 1021.1	2.81	0.4%
R7	S-7	933.2 1105.5	940.1 1114.1	604.7 717.1	2.78	0.8%
R8	S-8	2152.1 1930.5	2225.8 2030.4	1363.9 1215.0	2.43	4.3%
R9	S-9	1619.9 1486.2	1641.1 1511.7	1039.2 953.3	2.68	1.5%
R10	S-10	3707.3 982.1	3748.2 993.9	2380.3 631.9	2.71	1.1%
R11	S-11	935.5 1178.8	936.4 1180.2	595.7 750.1	2.74	0.1%
R12	BR-01	966.1 2445.0	968.3 2449.9	604.4 1529.9	2.66	0.2%
R13	GR-1	2778.4	2818.5	1783.8	2.69	1.4%
R14	GR-2	2780.7	2856.4	1785.7	2.60	2.7%
R15	GR-3	3090.3	3122.8	2009.9	2.78	1.1%
R16	GR-4	3085.3	3096.1	1995.1	2.80	0.4%
R17	GR-5	2662.6	2832.0	1671.1	2.29	6.4%
R18	GR-6	2856.5	2894.5	1849.3	2.73	1.3%
R19	GR-7	2885.4	2954.0	1839.7	2.59	2.4%

Table 5.3 Wetting-Drying Test Results

Rock Number	Test Sample Number	Initial Mass (g)	End of Test Mass (g)	Percent Loss
R1	S-1	3199.4	3199.1	0.0%
R2	S-2	3015.2	3015.1	0.0%
R3	S-3	3094.7	3094.4	0.0%
R6	S-6	3184.6	3184.4	0.0%
R7	S-7	3123.7	3123.5	0.0%
R8	S-8	2688.1	2687.4	0.0%
R10	S-10	2965.4	2965.2	0.0%

Table 5.4 Freezing-Thawing Test Results

Rock Number	Test Sample Number	Initial Mass (g)	End of ASTM Test Mass (g)	ASTM Percent Loss	End of Extended Test Mass (g)	Total Test Percent Loss
R1	S-1	2843.2	2841.3	0.1%	2839.3	0.1%
R2	S-2	2730.7	2618.9	4.1%	2507.5	8.2%
R3	S-3	3001.3	2968.6	1.1%	2856.7	4.8%
R4	S-4	2484.3	2484.0	0.0%	2484.0	0.0%
R5	S-5	2437.1	2436.9	0.0%	2436.7	0.0%
R6	S-6	2832.5	2832.5	0.0%	2828.5	0.1%
R7	S-7	2753.2	2753.2	0.0%	2750.6	0.1%
R8	S-8	2605.8	2604.4	0.1%	2591.7	0.5%
R9	S-9	2633.8	2569.0	2.5%	2402.8	8.8%
R10	S-10	2707.1	2629.8	2.9%	2510.0	7.3%
R11	S-11	2963.4	2963.4	0.0%	2963.4	0.0%
R12	BR-01	2921.6	2921.6	0.0%	2921.6	0.0%
R13	S-1	2778.4	2777.6	0.0%	2776.3	0.1%
R14	S-2	2780.7	2480.9	10.8%	2448.2	12.0%
R15	S-3	3090.3	3072.0	0.6%	3049.7	1.3%
R16	S-4	3085.3	3075.6	0.3%	3064.7	0.7%
R17	S-5	2662.6	2655.6	0.3%	2646.9	0.6%
R18	S-6	2856.5	2847.7	0.3%	62.8	97.8%
R19	S-7	2885.4	2872.4	0.5%	2861.4	0.8%

Table 5.5 Iowa Pore Index Test Results

Rock Number	Test Sample Number	Sample Mass (g)	Reading at: (ml) Initial 0 min.	1 min.	15 min.	Primary Load (ml)	Iowa Pore Index (ml)
R1	S-1	4500	7	23	33	32	20
R2	S-2	4500	7	31	54	48	46
R3	S-3	4500	9	30	50	42	40
R6	S-6	4500	9	22	27	26	10
R7	S-7	4500	6	25	38	38	26
R8	S-8	4500	7	108	111	202	6
R10	S-10	4500	9	26	42	34	32
R12	BR-01	4500	39	60	60	42	0
R13	GR-1	9000	0	68	78	68	10
R14	GR -2	9000	0	122	152	122	30
R15	GR -3	9000	0	23	50	23	27
R16	GR -4	9000	0	19	35	19	16
R17	GR -5	9000	0	231	238	231	7
R18	GR -6	9000	0	44	95	44	51
R19	GR -7	9000	0	102	120	102	18

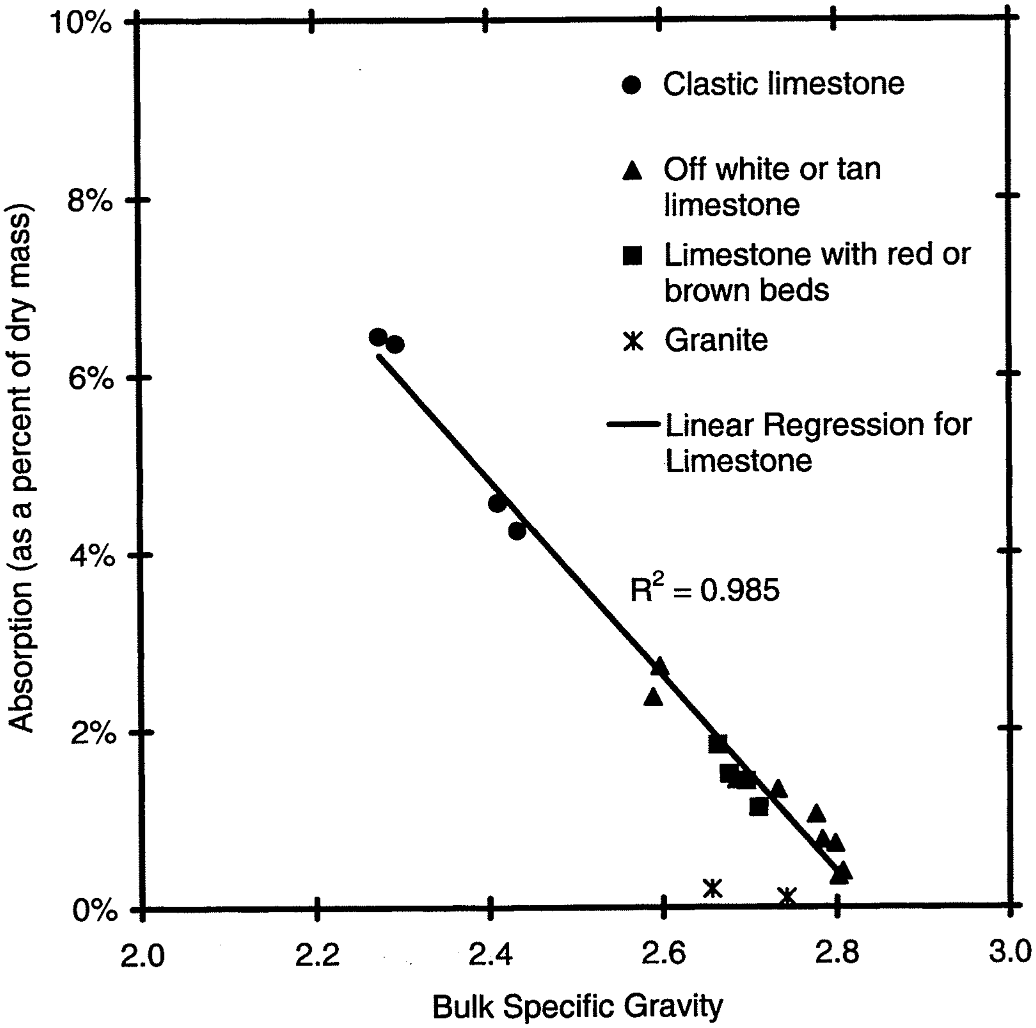

Figure 5.1 Bulk Specific Gravity versus Absorption

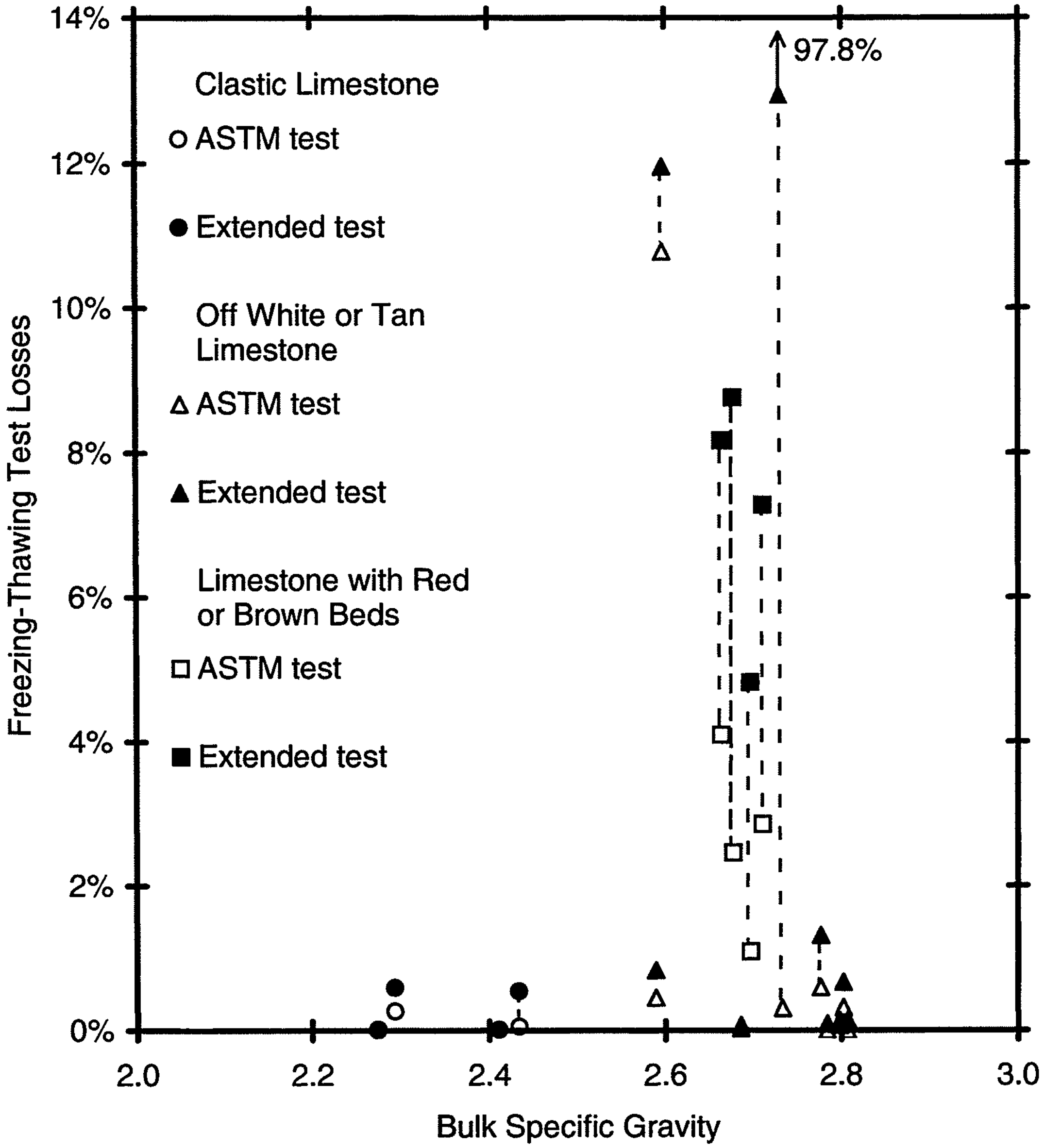

Figure 5.2 Bulk Specific Gravity versus Total Freezing-thawing Losses

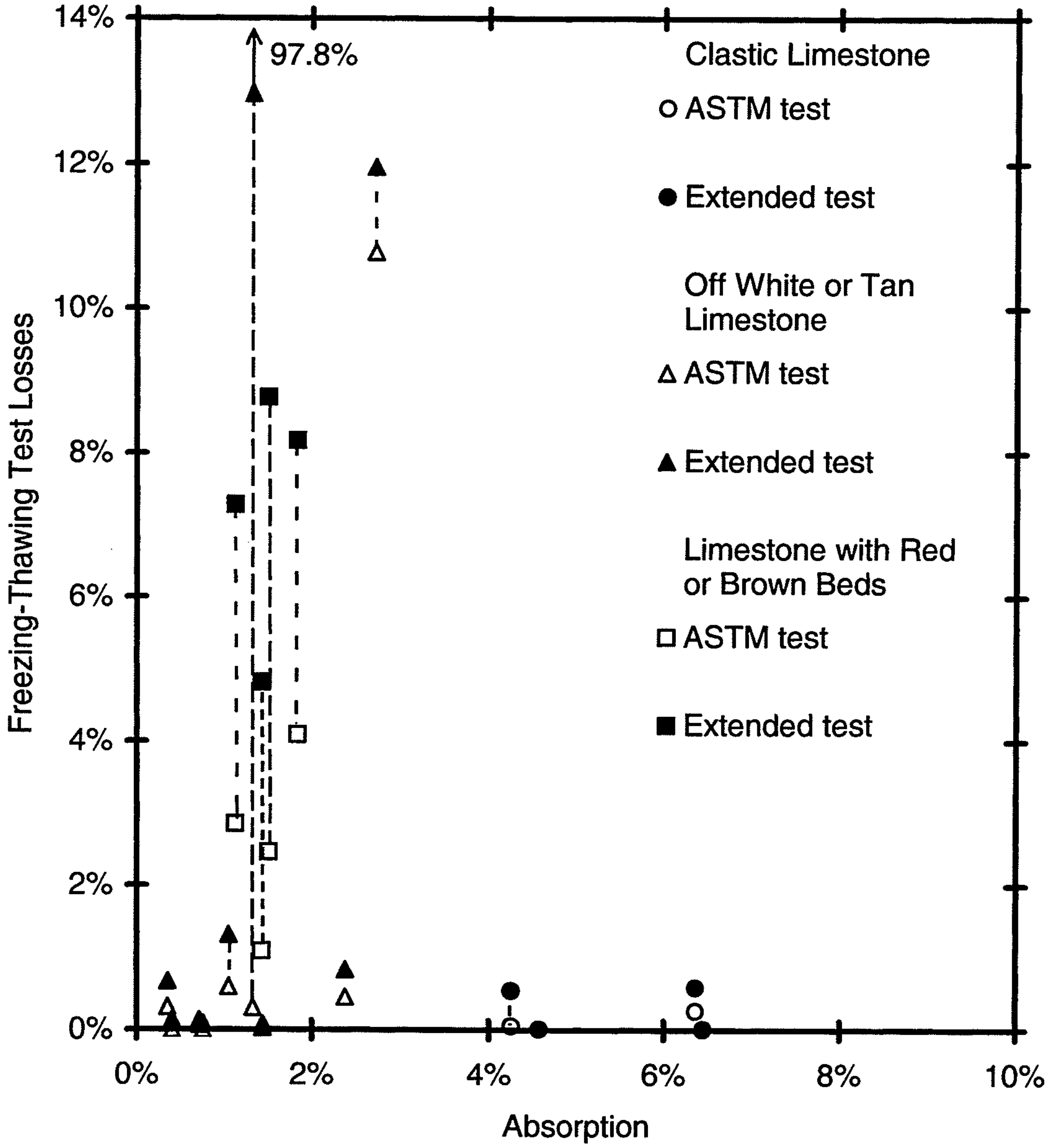

Figure 5.3 Absorption versus Total Freezing-thawing Losses

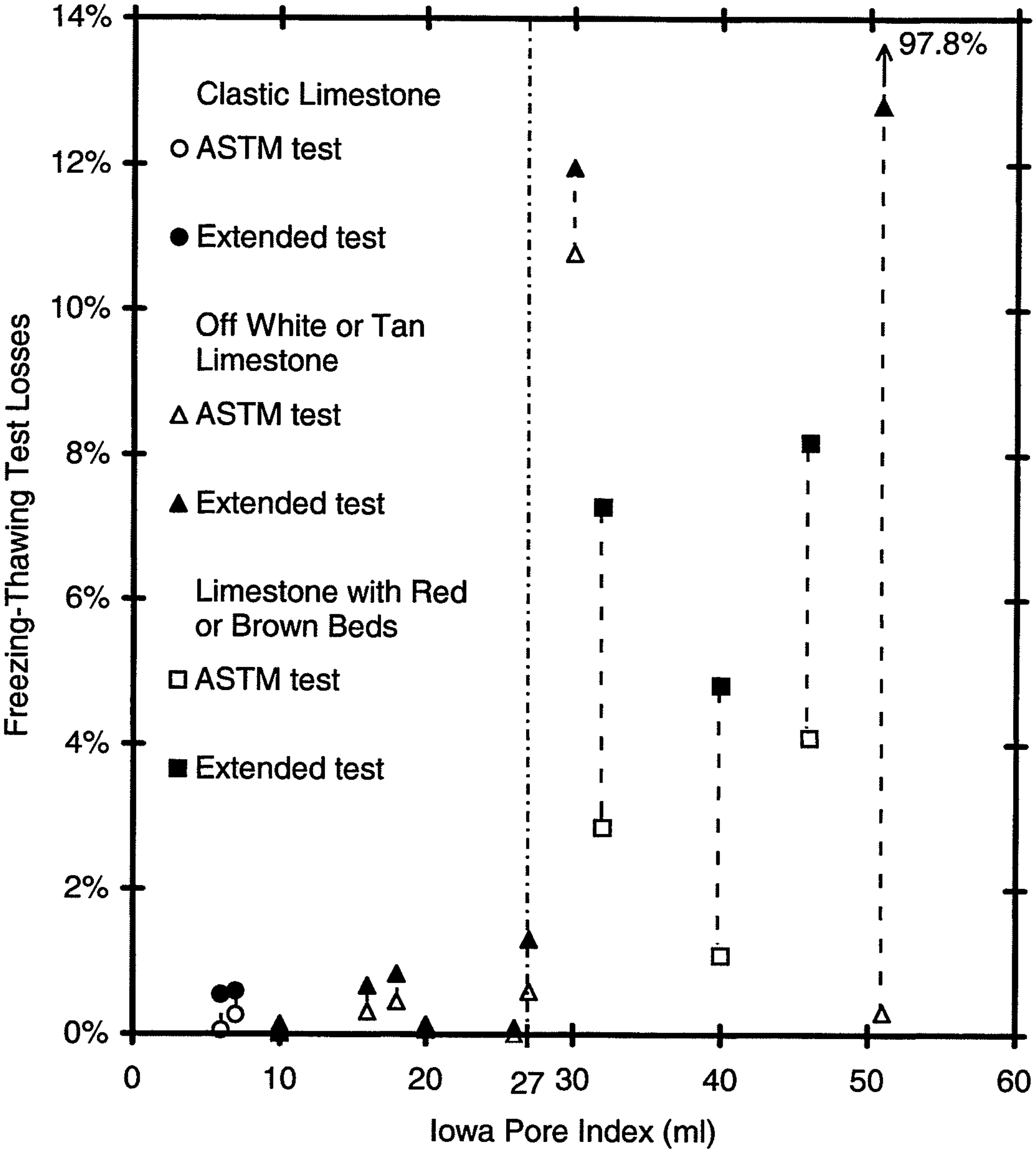

Figure 5.4 Iowa Pore Index versus Freezing-Thawing Test Losses

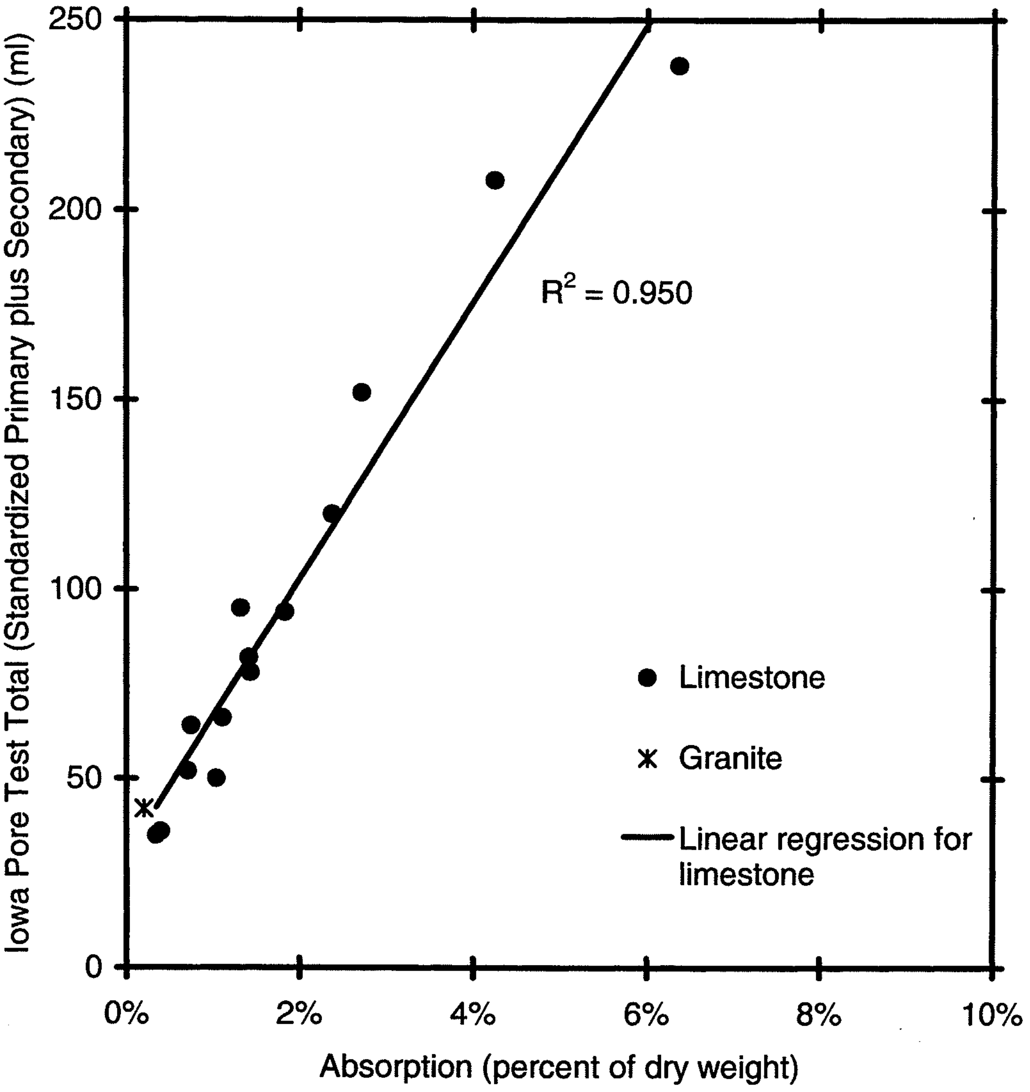

Figure 5.5 Absorption versus Iowa Pore Test Total

Chapter 6: Riprap Performance

6.1. Introduction

Performance of riprap is governed by the demands placed on it and its capacity to protect the dykes from these demands. The capacity of the riprap is controlled by its physical properties. The size and number of pieces of riprap at each section of the dyke system generally represent the capacity, while environmental forces directed against the riprap represent the demand. The capacity data are quite variable along the dyke system, possibly as a result of both the nature of limestone and the research methods that were used.

The riprap studied was originally taken from several quarries close to the dyke system. It is likely that the material should be quite similar from quarry to quarry as the limestone is layered horizontally in the area, although the classification and laboratory tests showed some variations in the riprap properties from location to location.

The size of the dyke system is relatively large (24 km in length) and restrictions in time and budget meant that only a very small sample of the total riprap cover could be analysed. Since this research is dealing with natural processes that varied locally along the dykes, the relatively small sample size of 80 grids, 3m x 3m, may not be considered fully representative of the available protection. As far as possible, efforts have been made to relate local measurements of riprap capacity with local environmental conditions, and therefore with local demand. There was also difficulty in measuring the masses of the rock samples taken from the dyke. As discussed in Chapter 4, the size that could be weighed was restricted by what could be lifted. To improve the data, rocks across the dyke system could be weighed by crane with a more sensitive load cell, with the masses being measured both in air and in water.

As a result of the significant variability of the data, the interpretation in following sections must of necessity be qualitative and subjective. Judgement is needed to reach conclusions with these data.

For assessing the capability of the riprap to provide protection, it is necessary to compare riprap capacity to the local demand, generally represented by the size of the waves impacting the dyke at that location. This is a useful measure, but it is difficult to use the size of waves themselves to determine whether the dyke system is at risk of erosion. A better procedure, and the one that is used for designing riprap protection, is to convert the size of the waves to the D_{50} size required to protect the dykes. This size can then be compared with the available D_{50} to determine which sections are not adequately covered by riprap and are therefore at risk of erosion.

6.2. Capacity

The capacity of the riprap pieces to protect the dykes from erosion is comprised of a number of factors that vary considerably from point to point along the dyke face. The factors that protect a selected area of the dyke face include:

- the average size of the individual large rocks protecting an area,
- the number of rocks in that area,
- the mass of the rock,
- the amount of void space that is not covered by adequate rock, and
- whether there are adequate small rocks to fill in the gaps between the larger rocks yet not be removed or degraded by wave action.

The most obvious factor missing from the preceding list is the durability of the individual rocks. For the site that forms the basis of this research, durability was tested in the laboratory and the results were discussed in the previous chapter (Chapter 5). Durability has a significant effect on the ability of individual rocks to maintain their size and better protect the dykes. Budget and time restrictions restricted the amount of laboratory testing that could be done to create a data base of durability across the entire dyke system. If the scheduling for this research had allowed laboratory testing to precede the field study, both the laboratory results and the rock descriptions provided by the owner's geological engineer would have been useful during the field study. As a result of these limitations, the data are not sufficient to permit evaluation of durability issues at all sections of the dyke system. As a result, the treatment of mechanical durability has been restricted to the laboratory tests described in Chapter 5. It will not be considered directly in this section, which deals only with capacity and demand relationships.

As discussed in section 6.1, there were some limitations to the data generated in this study. Despite the difficulties resulting from these limitations, the following principal conclusions arose from the presentation and discussion of the field data in Chapter 4. They represent the capacity of the riprap to protect the dyke from the environmental demands placed on it.

6.2.1 Mass

The 'amount' of large rocks providing protection for the dyke face is perhaps best represented by the mass of the large rocks over the area of the dyke face. This is not the measurement that is typically used in design, but it takes into account both the number and size of the rocks covering the dykes. It is calculated by finding the volume of every measured rock within the grid, converting that into mass, totalling the mass for the whole grid and dividing by the area of the grid.

In this research project, the mass of rock per unit area varies significantly across the dyke system. This can be seen in Figures 4.15.a through c. Although there is a large amount of scatter in the data, as is apparent by the low R^2 values, there appear to be trends along some of the dykes. The mass varies between 93 kg to 1011 kg per square meter. Some sections of the dykes seem to have generally higher masses, while others are generally lower. Over most of the dykes, the mass decreased from 1998 to 2001, but the amounts of the reductions vary considerably. One section actually seems to have increased its mass lightly (clearly due to measurement inconsistencies), while another section had a decrease of about 400 kg.

6.2.2 Percent Void Area

The amount of void area indicates how much of the dyke face is exposed without cover and at risk of erosion. This was described in the 2001 field study by the percent of area within a grid that was not covered by rock larger than 0.1 m on two sides. The 1998 field study used a different measure for void area, which is not presented here. This percentage of void area by location was shown earlier in Figures 4.11.a through c. As previously described, the void area varies significantly from 5% to 90% with generally a large variability from one site to the next. The trend lines generally have very low R^2 values, but some seem to indicate areas with generally low amounts of void spaces and other areas where void spaces seem to increasing or decrease more or less systematically across the dyke system.

6.2.3 Number of large rocks

The number of large rocks contributes to the capacity of the riprap since a greater number of rocks should generally mean that more of the area is covered by riprap and protected. It is the simplest and most objective of the measurements taken and should provide the most consistent results from year to year. The number of large rocks by location in the dyke system as found in the field study is presented in Figures 4.12.a through c. The data are again quite variable, but trends from along the length of the dykes indicate an increase in the number of rocks from 1998 to 2001, rather than a decrease. The increases are greatest for Dyke 2 North and Dyke 2 South.

6.2.4 Size (D_{50}, Ave. Nom. Diameter)

The average nominal diameter and D_{50} are two separate means of calculating an average size of the riprap. These are discussed in Chapter 4 results can be seen in Figures 4.13.a through c and 4.14.a through c. The nominal diameter is the cubed root of the dimensional volume of the rock and an average is calculated for the rocks at a particular location. Meanwhile, the D_{50} is the 50th percentile rock, by mass, based on the intermediate dimensions of the rocks measured at that location. Again these are highly variable from location to location, but trends can again be seen from dyke to dyke. The most notable observation here is that while the number of large rocks increased with time, their average nominal diameter and D_{50} decreased.

6.3. Demand

The demand on the riprap relates to various environmental impacts, which work to breakdown the size of the riprap. These include a number of impacts such as wave energy, wind blown particles, plants and living material, chemical changes in the rock, freeze-thaw damage, and ice movement. Each of these impacts breaks down the protection provided by the rock. The impacts can degrade the exterior of the rock so that the rock becomes smaller, break the rock into two or more smaller rocks, or physically remove the rock to another position where it is less able to absorb wave energy.

This section deals with the wave energy directed at the limestone riprap, as represented by wave height. Wave heights are derived from the speed of a wind event and the length of reservoir available to generate waves, that is 'fetch'. Increasing the fetch or the wind event, holding the other constant, creates greater wave heights. The maximum wave height at any one site can vary significantly as the wind may be stronger in one direction, but over a longer fetch in another.

To reduce the number of calculations to a manageable amount, wave heights were calculated for selected grid stations in intervals approximately 1 km or where significant changes in direction or fetch occurred. A total number of 36 sites were selected for wave height calculations.

Wave heights were first determined in the direction of the prevailing wind, then in a variety of directions based on recorded wind speeds and fetches measured in a radius of 84 degrees. (This radius was chosen for convenience, based on the calculations for effective fetch, explained in section 6.4).

6.3.1 Fetch Lengths

Fetch lengths have been taken as the distance from the dyke face, where the wave height is to be calculated, to the opposite shoreline across the reservoir basin. The fetch length is often measured in the direction perpendicular to the dyke face. However, this may not produce the largest waves since wave generation is also affected by wind speed, which varies considerably in different directions. To capture the possible variations in wave height, fetches were measured in a series of radial directions starting in a direction at perpendicular to the dyke face and measuring the fetches in seven additional directions at intervals of 6° on each side of the perpendicular direction. This process produced a total of 15 fetch directions in a fan of 84 degrees. The fetch in the compass direction of the prevailing wind was also measured. Figures 6.1.a through c summarises results for the longest fetch, the fetch perpendicular to the bank and the fetch in the direction of the prevailing wind. The maximum measured fetch at the research site is 19.3 km and the shortest is 53 meters. These fetch distances are generally longer for sections furthest away from Station 0+00 and shorter as they get closer to Station 0+00.

It should be noted that the procedure described earlier for calculating radial fetch distances might not capture the longest fetch in each case. The opposing banks are very irregular in nature and the problem of finding the longest fetch is arduous. These intervals simplify this problem, but may not capture all possible fetches. These intervals were chosen for convenience and are the same used for calculating effective fetch, as explained in section 6.4.

6.3.2 Wind Speeds

For the design of riprap, the largest or prevailing wind is often taken as the dominant wind speed, but if the fetch length in the direction of the prevailing wind is relatively small, this wind speed may not necessarily result in the greatest wave heights. At this dyke system, the dykes face in such a way that they may be affected by waves generated in the direction of the prevailing wind. However, many of the dykes do not directly face the prevailing wind and many have relatively short fetches in the direction of the prevailing wind. In such cases, it is possible that the largest waves may not be generated from the wind in the direction of one of the longer fetches.

Since wind speed varies continuously with time and direction, a wind rosette is used to determine the wind speed for wind events with specified return periods. A wind rosette combines site-specific information about wind direction and magnitude, allowing the user to find wind speeds in any direction for specific storm return periods. In this case, the 100-year return period was chosen, since many of the dykes have long fetches (the average is greater than 8 km) and those dykes with shorter fetches are often quite high (up to 30 m in height).

According to an unpublished wind rosette for the local area, provided by the owner, the prevailing wind speed, for a wind event with a 1 in 100 year return period, is 85.9 km/hr over land. The rosette lists the wind speeds in 8 compass directions and does not allow for interpolating between these directions. As a result the wind speeds must be related to the radial fetches using the closest wind speed in the compass direction of that radial. Table 6.1 presents the wind speeds for events occurring with a 1 in 100 year return period, as according to the wind rosette for the local area. The highest wind represented by the rosette is the prevailing wind at 85.9 km/hr, while the lowest is 51.0 km/hr.

The wind speed is further complicated by the fact the wind speed measurements represented by the rosette were generally taken over land, while waves are generated by wind speed over water. The latter is generally greater than the wind speed over land, since water has significantly less roughness. The speed of the wind actually increases as it crosses water, so where the fetch is longer, the wind speed over water is greater. Since the fetch varies considerably, the wind speed over water must be calculated at each dyke location.

Wind speeds over water were calculated based on the graphical method described in Acres (1988). Some of these results can be seen in Figures 6.2.a through c, which shows the largest wind speed over water event at the selected locations and the wind speed over water for the event perpendicular to the dyke face.

These wind speeds over water again vary significantly since the length of fetch and the direction the dyke faces vary from location to location along the dykes. The highest wind over water occurs in the direction of the prevailing wind and longest fetch in that direction, which is 113 km/hr in Dyke 2 North. The minimum wind speed found over water is 52.3 km/hr, which is the lowest wind speed event, coupled with a small fetch in again in Dyke 2 North.

6.3.3 Wave Heights

As described in previous sections, wave heights are affected by wind speed and fetch distance. Each measured radial fetch distance is related to the appropriate wind speed based on the compass direction of that fetch, so typically at each location, the radial fetches are split into two or three compass groupings for each wind event speed. A wave height was calculated for only the longest fetch in each compass grouping, as this will produce the largest waves for that wind event.

Figures 6.3.a through c show wave heights found from the fetch distance and wind event speed using the graphical method described in Acres (1988). The figures show wave heights created by the prevailing wind and the fetch in that direction. They also show the maximum waves created by winds in the radial fetch directions. Wave heights are seen to vary considerably across the dyke system but some patterns are also evident. The highest waves are along Dyke 2

North (3.0 m), which are related to high prevailing winds and long fetch distances. The lowest waves are at Dyke 1 North at 0.7 m, which are in a more protected area.

In some cases the wave heights created by the prevailing wind are larger than those created by the radial fetches, since the prevailing wind is outside the compass direction of the radial fetches. At each location, the greatest demand on the riprap has been associated with the maximum wave height generated by either the prevailing wind or the radial fetches.

6.4. Design Size of Riprap

The demand on the dyke system can also be analysed in terms of the size of riprap required to protect dykes during storm events that generate the maximum wave heights described in the previous section. This "required" size can then be related to the "available" size to evaluate adequacy of protection against wave damage. Section 6.2 showed existing capacity (or "available" size) along the dykes, while Section 6.3 developed the "loading" that can come on to the dykes at each location in the form of maximum wave heights. Now the size of riprap that is needed to withstand this loading must be identified.

There are a number of different design methods available for determining the required or design size of riprap for a dyke system. As discussed in Chapter 2, the well-established Hudson's formula is by far the most popular method. It produces a required riprap size in terms of D_{50}, which is commonly used as the size criterion during construction. Where the various design methods differ is in their selection of the properties used for this formula. A designer must face the question of which storm/wind events, fetch distances and wave heights are most appropriate to accurately describe the conditions at the site, and which must therefore be designed for.

Acres (1988) recommended using an "effective" fetch and the prevailing wind speed to calculate the design wave height and design D_{50}. The "effective" fetch refers to a distance calculated using an averaging method similar to the radial method described in the previous section for estimating fetch distances. It takes into account the variety of possible fetch distances over a range of directions. The prevailing wind speed is applied across the dyke system, regardless of the direction of the individual dyke faces. As previously mentioned, the Acres (1988) report recommends using the 50-year return period for smaller dams. However, since the size of the reservoir being considered in this research is significantly large, the 100-year return period has been used. Values of design wave height and D_{50} have been calculated for each dyke section where there is a change in fetch.

Details were given in the previous section for calculating effective fetch distances by drawing 15 radials from the dyke face to intersect with the shoreline across the basin. From the 15 radial fetch distances, the effective fetch is found using:

$$\text{Effective Fetch} = \frac{\sum_{k=1}^{15} x_k \mathrm{Cos}^2 a}{\sum \mathrm{Cos}\, a} \qquad [6.1]$$

where:

X_k = fetch length of 1 of 15 radials, and

a = angle from the current radial to central radial (Saville et al. 1962, Acres 1988).

This calculation was completed for the same selected locations as listed in the previous section. The resulting effective fetches for the study dyke system are shown in Figures 6.1.a through c. The maximum effective fetch distance from these calculations is 8.2 km and the minimum is 0.43 km. Notice that these fetch distances are significantly different from the fetches used in the last section for evaluating maximum wave heights. Here, for calculating D_{50}, the averaging method weights the fetches in the perpendicular direction very heavily. The result is that if the perpendicular fetch is short, the effective fetch tends to be short, even when some of the other radials are relatively long.

As mentioned in the previous section, the 1 in 100 year return period wind speed over land for the prevailing wind is 85.9 km/hr. Again, this is converted into wind speeds over water, based on the individual effective fetch for each selected location and using the graphical methods described in the Acres report (1988). The maximum wind speed event over water is 119 km/hr, a value that is slightly higher than in the last section because in design, the prevailing wind is applied to all fetches, whether or not they are in the direction of the prevailing wind. In the study location, some of the longest fetches do not face the prevailing wind, so the design calculation results in a larger wind-over-water event, than the one produced by the actual wave event.

These effective fetches and wind speeds over water have again been converted to wave heights using the Acres (1988) recommended graphical method. The resulting wave heights are shown in Figures 6.3.a through c. They are generally not as high as those found in the previous section, since the effective fetches tend to be lower on average than the measured fetches. The maximum wave height is 2.4 m and the minimum is 0.5 m.

As discussed in Chapter 2, Hudson (1949) developed the following expression to determine the weight of rock required for protecting against damage:

$$W_{50} = \frac{\gamma_r H_s^3}{K_D (S_r - 1)^3 \operatorname{Cot} \theta} \qquad [6.2]$$

Where:

W_{50} = minimum weight of the median sized rock,

γ_r = unit weight of the rock,

H_s = design or significant wave height,

K_D = stability coefficient, which varies with size and shape of rock and type of waves,

S_r = specific gravity of rock, and

θ = angle of dyke slope from horizontal.

In this study (Chapter 4), the field investigations found the average unit mass density of the rock 2519 kg/m^3 and the average specific gravity was 2.63. The stability coefficient chosen was 2.2, which according to Acres (1988) is recommended for large dykes of this size. The angle of the dyke slope from horizontal, according to unpublished reports from the owner, is 21.8 degrees. Hudson calculations (Equation [6.2]) were completed at each of the 36 locations where wave heights had been evaluated.

The values of W_{50} from [6.2] were converted to the corresponding D_{50} using the equation:

$$D_{50} = \frac{W_{50}}{\gamma_r} \qquad [6.3]$$

where:

D_{50} = required average diameter of the median rock found by weight,

W_{50} = weight of the median sized rock, and

γ_r = unit weight of the rock.

These D_{50}'s vary considerably from one reach of the dyke system to the next (Figures 6.4.a through 6.4.c). The variability appears to follow a pattern within each of the individual reaches of the dykes, tending to be lower towards the centre of the North and South Dykes, and higher at the further Stations. These "required" sizes from Equation [6.3] can now be compared with the "available" sizes found in Chapter 4 to evaluate the adequacy with which the current riprap provides protection against wave damage.

6.5. Capacity – Demand Relationship

Methods of comparing the available capacity (discussed in Section 6.2) to the demand capacity (discussed in Sections 6.3 and 6.4) must now be considered. The available capacity can be expressed in a number of different ways that include (among others), the amount of coverage provided by the rocks, and the average size of those rocks. There are two main sets of data to be compared when considering the demands on the riprap. One, the demands resulting from the calculated maximum wave heights (Section 6.3) can be compared to the capacities in terms of the various measured and calculated properties discussed in Section 6.2. This study will plot capacity *versus* demand graphs and look for qualitative empirical relationships. Two, the demand and capacity can be considered more directly in terms of D_{50}, by comparing the 'required' or design D_{50} and the D_{50} measured on the dykes.

In the first set of empirically based comparisons of capacity and demand, there are a number of properties to be considered. Capacity can be expressed as the number of rocks, the average nominal diameter, the mass of rocks per square metre, and percent void space, all of which can clearly be qualitatively related to the ability of the riprap to protect against wave action.

In a similar way, demand can be expressed qualitatively by the maximum wave heights produced by the radial fetches with the expected 100-year *wind speed* in the respective radial direction. Alternatively, demand wave heights can be assessed from the prevailing wind and fetch. These two estimates of demand will produce different results. Since the prevailing wind is at a significant angle to the dyke at some locations along the site studied, two sets of figures were created. Generally, the maximum waves produced by considering only the radial fetches (with their corresponding wind speeds) are presented before the alternative method, which is based on the maximum waves calculated from either radial fetches or from prevailing wind and its fetch. Results of the qualitative studies are discussed in following paragraphs and the corresponding figures.

The number of large rocks per square metre in each of the study sections is plotted against the maximum wave heights calculated from the radial fetches in Figure 6.5. Although there is a very large amount of scatter in the data and the R^2 values are very low, the trend line for 1998 drawn through the data indicates the number of rocks appears to be relatively uniform regardless of the wave heights. The corresponding trend line for the 2001 data reveals a higher total number of rocks than 1998 and suggests the number of rocks increases slightly as the wave height increases, perhaps suggesting some breakdown of large rocks with high wave energies. Broadly similar results are seen in Figure 6.6, which now includes maximum wave heights found using the alternative method that includes consideration of the prevailing wind. (Some of the wave heights are larger than those in Figure 6.5 that used only the radial fetch distances.) In this case, there is less evidence of the number of rocks increasing with wave height, but the number of rocks appears somewhat larger, regardless of maximum wave height.

As discussed in Chapter 4, these results are at first sight counter-intuitive. It might be expected as the rocks break down, there would be fewer large rocks, especially in the areas of larger wave heights. It should be remembered that the number of rocks per unit area is not necessarily a good indicator of the degree of protection, but that the size of the rocks is a better gauge.

When sizes are related to wave heights (Figures 6.7 and 6.8), there is virtually no evidence that the average nominal diameters can be related to wave heights for either the 1998 or the 2001 data. (Figure 6.7 illustrates the effects of wave heights using just the radial fetches, while Figure 6.8 displays the maximum wave heights calculated from either the radial fetch directions or the prevailing wind and its associated fetch.) In spite of the large amount of scatter in the data, the trend lines in Figures 6.7 and 6.8 demonstrate a decrease in average nominal diameter between 1998 and 2001. Note that higher waves require larger average rock sizes. If the trend with time suggested in Figures 6.7 and 6.8 continues, at some point in the future, the current average nominal diameter may not be large enough to protect the dykes from wave action.

When examining the mass of large rocks per square metre, the data are again scattered (Figures 6.9 and 6.10). The trend line for 1998 appears relatively consistent regardless of the wave heights. Interestingly, though, the trend line for 2001 indicates that at smaller wave heights the mass is lower than the 1998 values, while at larger wave heights it is much closer to the 1998 values. This trend is more marked in Figure 6.9 which shows the waves from the radial fetches alone, and less evident in Figure 6.10, with lower R^2 values. Reasons for this apparent relationship are unclear at this time.

The percent of void space plotted against wave height (Figures 6.11 and 6.12) has even more scatter to the data than the previous figures, to the extent that statistical evaluation of the data must be considered questionable. The trend lines shown in the figures appear to indicate a decrease in void space with higher waves, but the high amount of scatter suggests this may be coincidence, not systematic.

The second method for evaluating the adequacy of the riprap is to compare measured values of D_{50} with 'design' values needed to provide protection against estimated 100-year wave events. Examples of these comparisons are also shown in Figures 6.4 a through c. These figures suggest that the current riprap may be significantly undersized in a number of locations along the dykes. There seems to be little evidence that the riprap is disintegrating more rapidly in areas where the demand is higher, but there does seem to be an overall pattern of some degradation of the riprap protection from 1998 to 2001.

Comparisons were also undertaken that grouped the locations based on their position on the dyke face, whether 'lower' near the average water level; or 'middle', half-way up the dyke face. These grouping provided no further useful insights and the figures have not been included.

6.6. Conclusions

Although the data show a significant amount of scatter, some useful relationships can be noted. It appears that the average D_{50} of the riprap has decreased in size from 1998 to 2001. During the same period, the number of 'large' riprap pieces has increased. Most of the results seem unrelated (or at best, poorly related) to wave height, so an alternative mechanism is required to explain the decreases in D_{50}. The riprap appears to be undersized in a number of locations along the dykes, suggesting a risk of erosion at times of high wave energy during storm events.

Although generally, the change in size and amount of riprap correlates poorly to the size of the waves directed against the riprap, it appears in certain cases, that there is perhaps a weak relationship between the number of riprap pieces and the size of waves. In these cases, the number of rocks appears higher in 2001, than in 1998, specifically in areas with larger waves. At the same time and for reasons that are unclear, there is some limited evidence that the mass of the rocks is decreasing at a slightly greater rate in areas with smaller waves. However, confidence in this association is inhibited by the wide scatter in the data (the R^2 values are very low).

The changes in size and number of the rocks was also discussed in Chapter 4 where it was proposed that freeze-thaw attacks could be splitting larger rocks into two or more smaller rocks, that are still large enough to count as 'large'. The largely independent nature of the measured amount (mass and size) of rock to wave heights deduced in this chapter complements this splitting theory. The observations suggest that splitting may be due more to environmental effects such as freezing-thawing than to the effects of energy dissipation during storm events. (The laboratory data in Chapter 5 suggest that wetting-drying will not produce significant amounts of degradation with this particular limestone riprap.) In summary, the observed degradation appears to be related to the durability of the limestone in terms of freezing-thawing processes and local variations in durability of the limestone across the length of the dyke structure.

Table 6.1 Wind Speed

Direction	Wind Speed for 1 in 100 Year Return Period Event (km/hr)
North	61.3
North-East	59.4
East	51.0
South-East	62.2
South	52.3
South-West	85.9
West	71.6
North-West	84.3

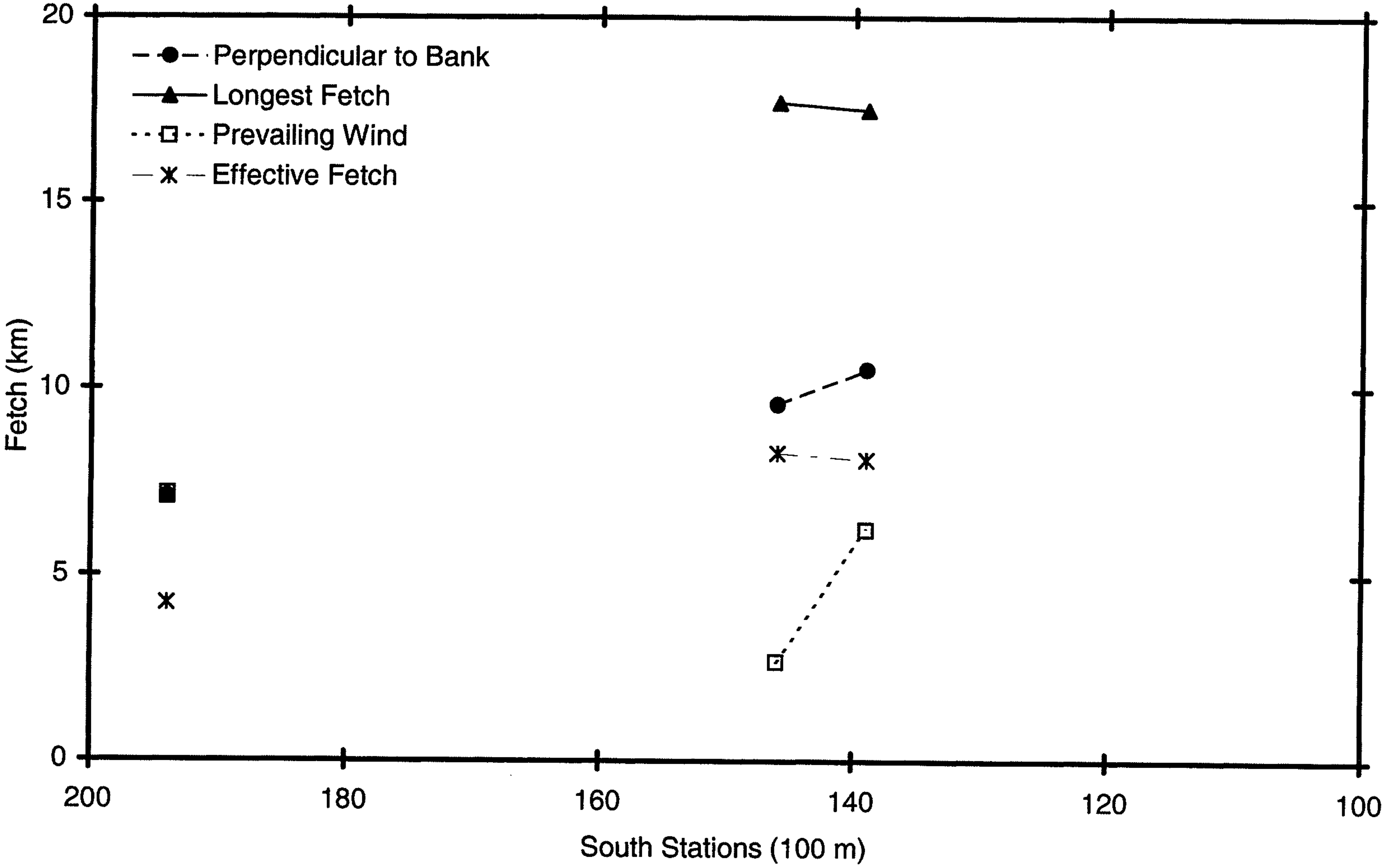

Figure 6.1.a Fetch Distances, Dykes 3 and 4 South

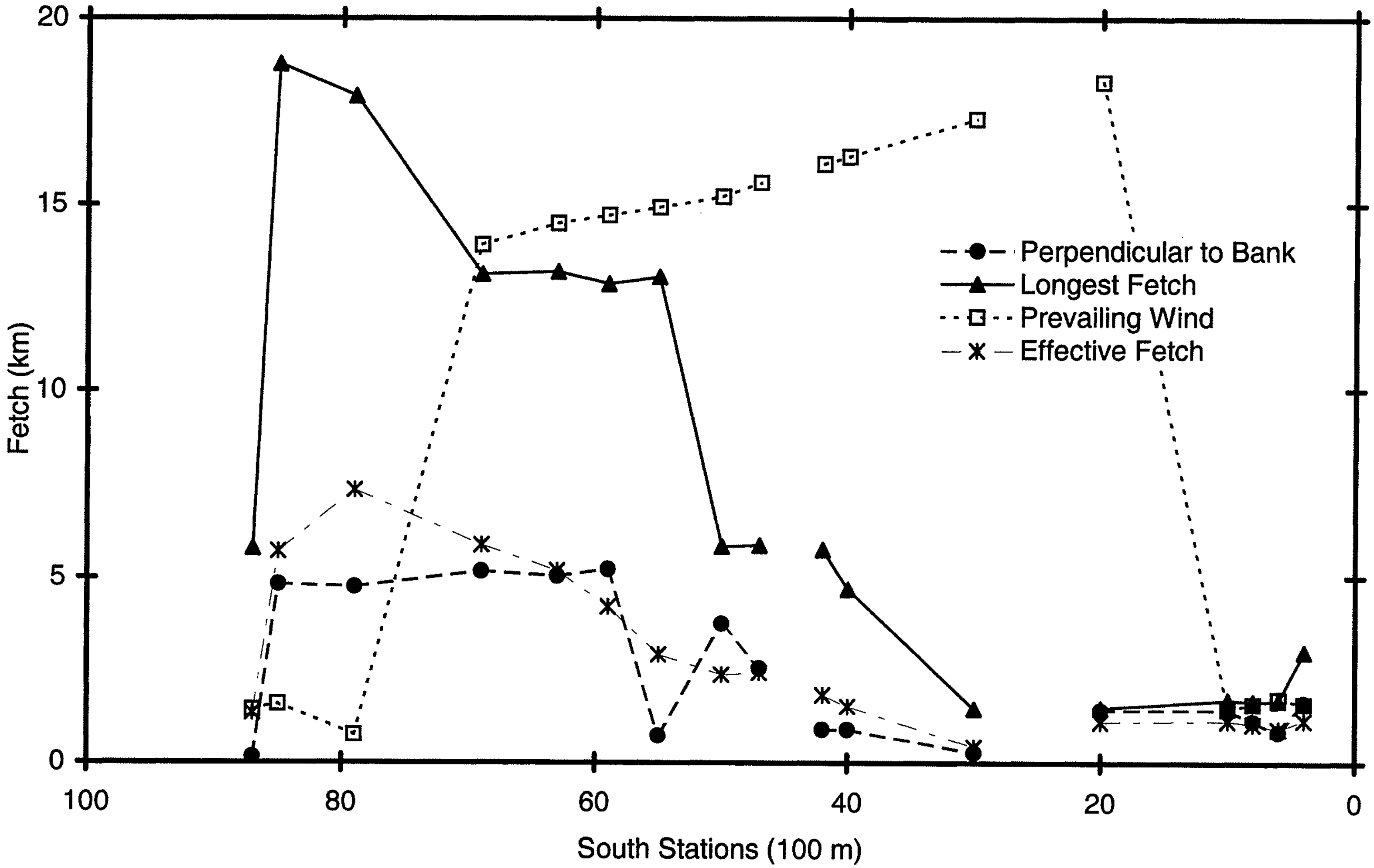

Figure 6.1.b Fetch Distances, Dykes 1 and 2 South

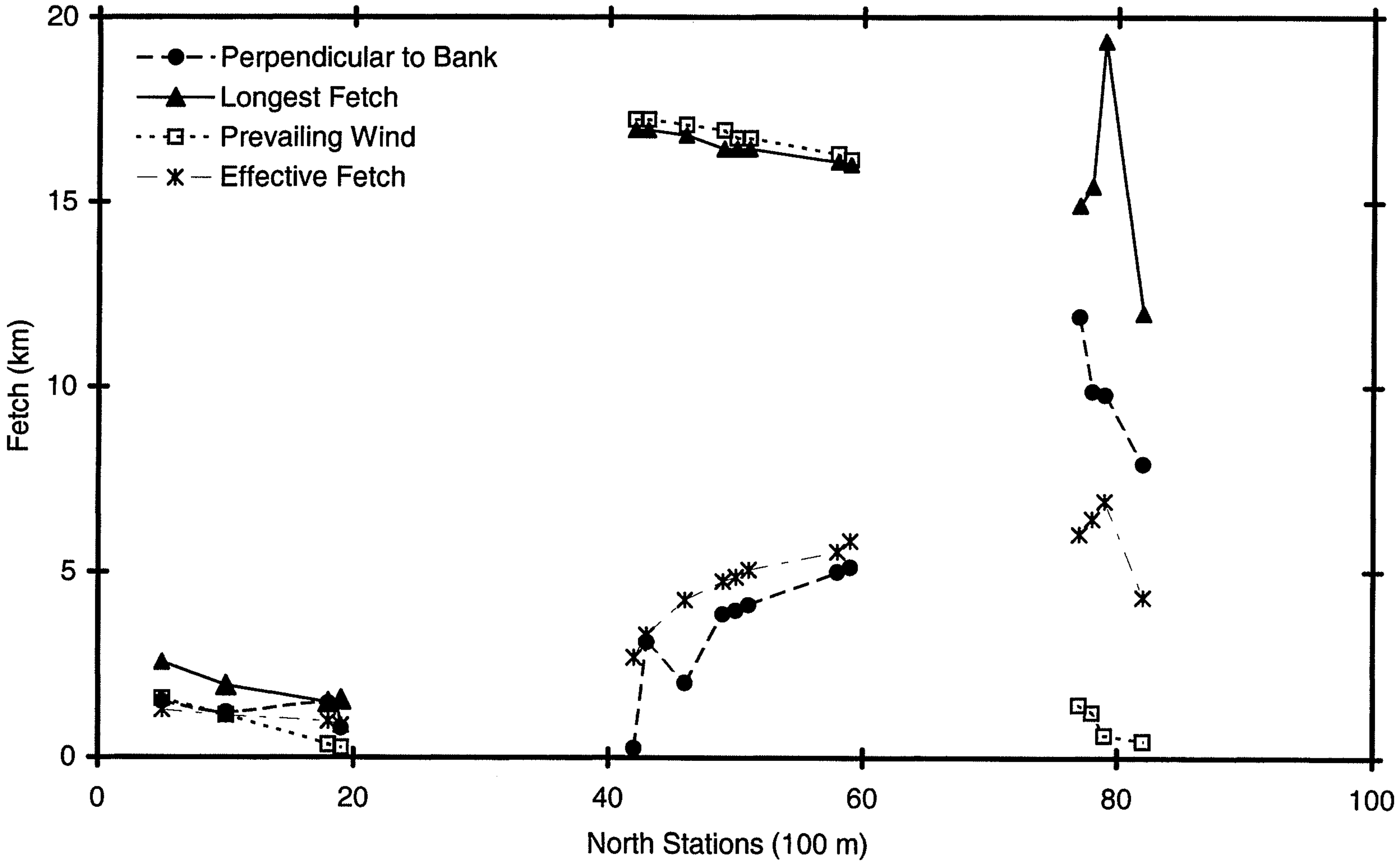

Figure 6.1.c Fetch Distances, Dykes 1 and 2 North

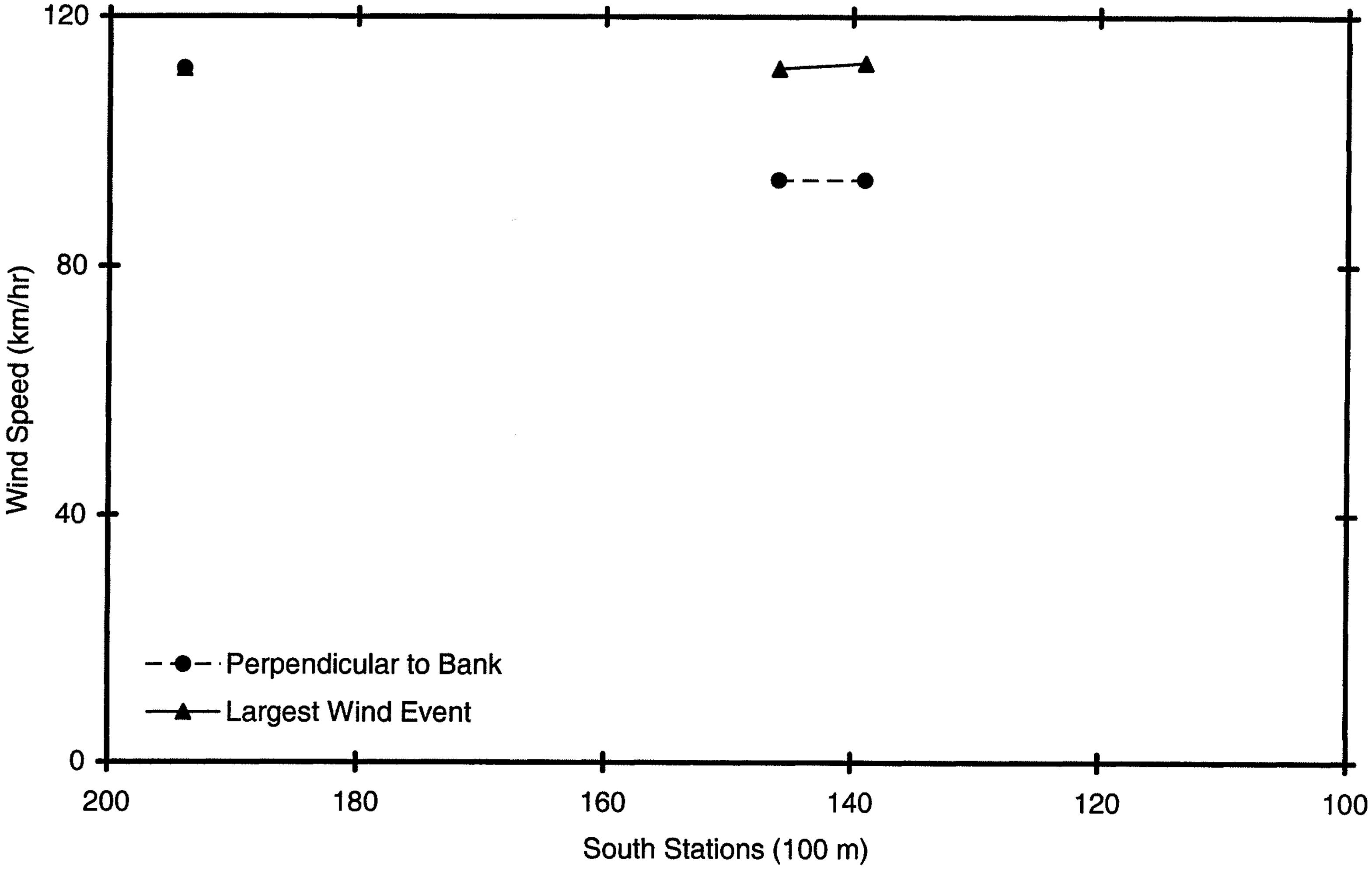

Figure 6.2.a Wind Speed Over Water, Dykes 3 and 4 South

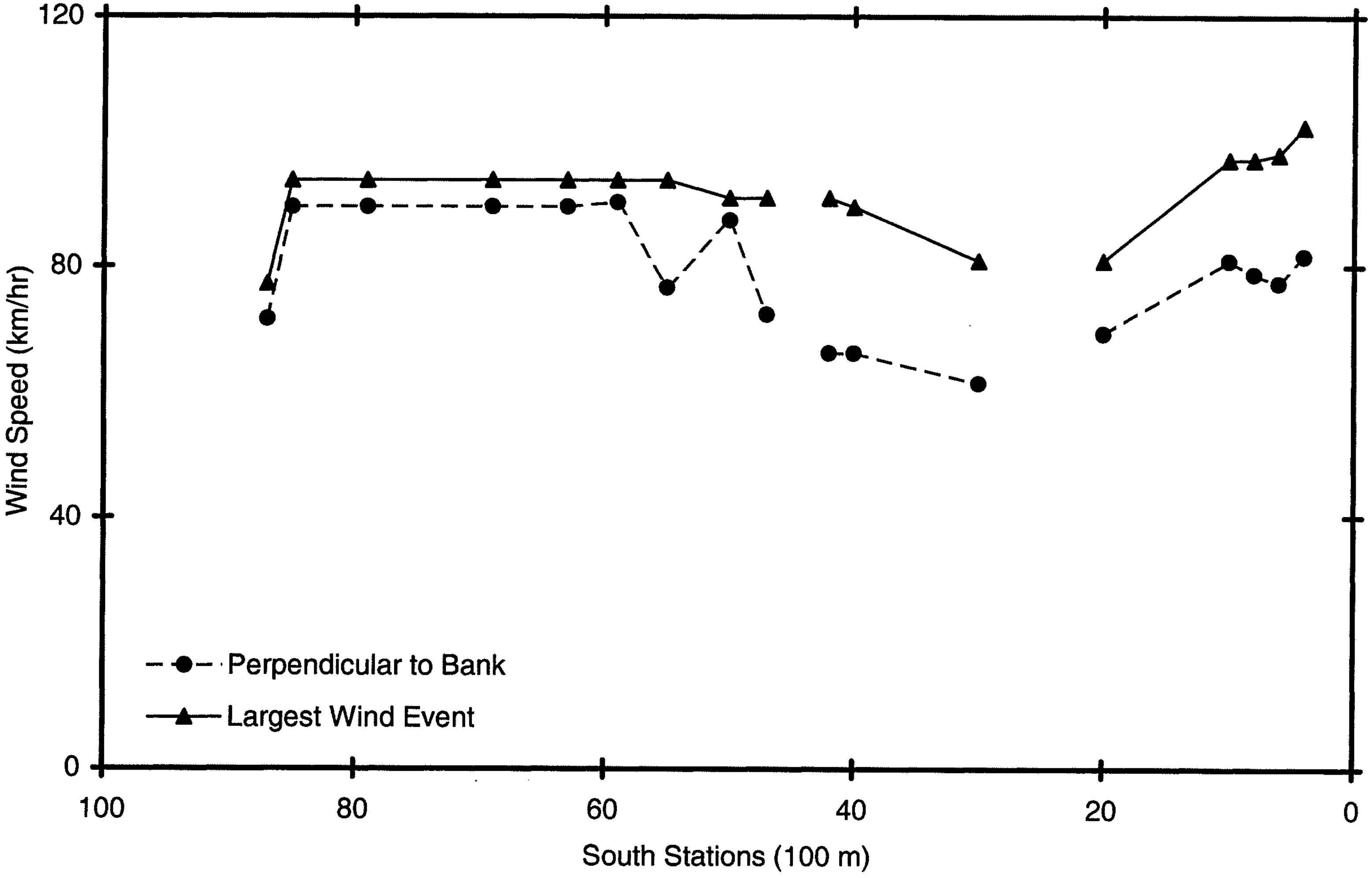

Figure 6.2.b Wind Speed Over Water, Dykes 1 and 2 South

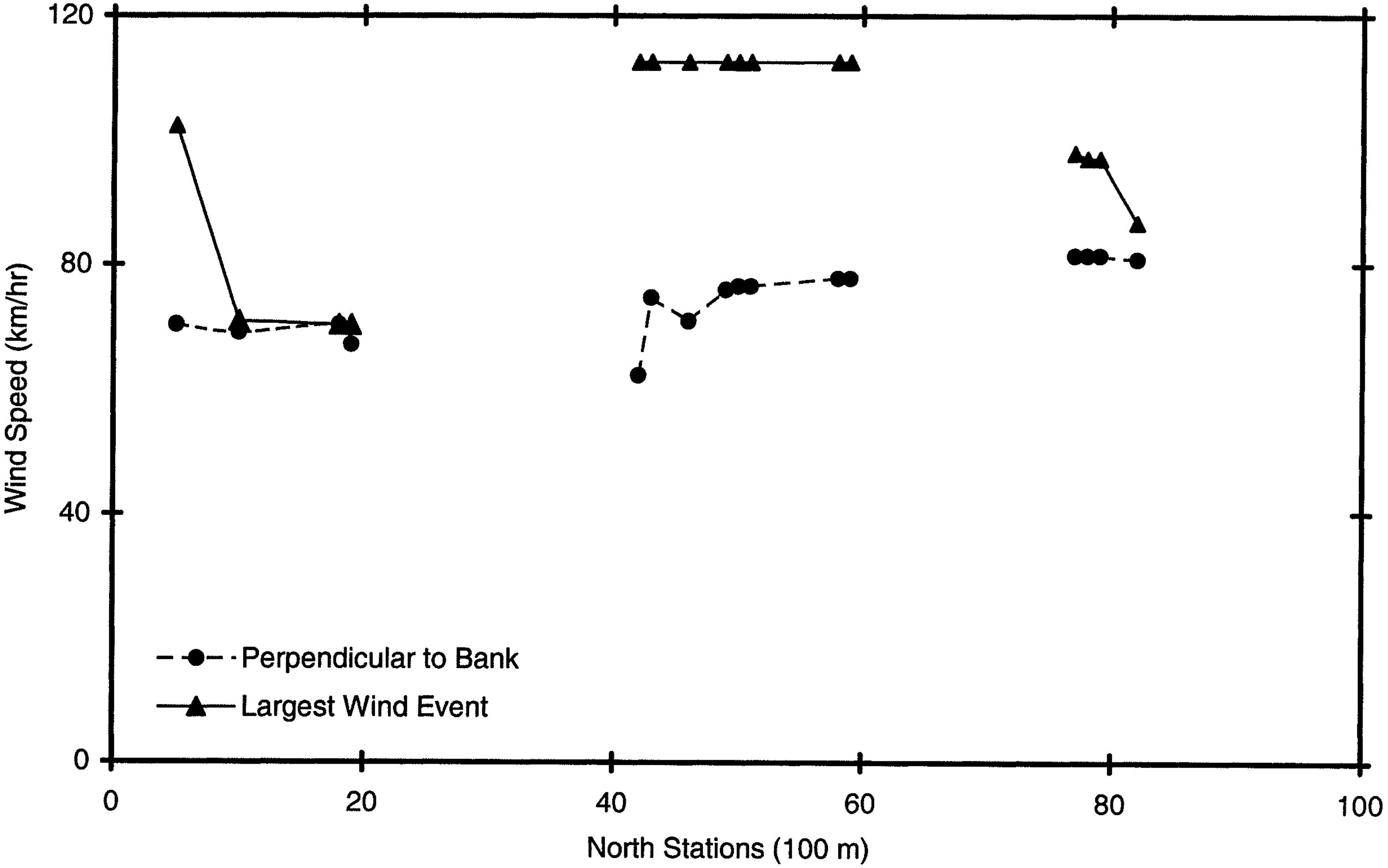

Figure 6.2.c Wind Speed Over Water, Dykes 1 and 2 North

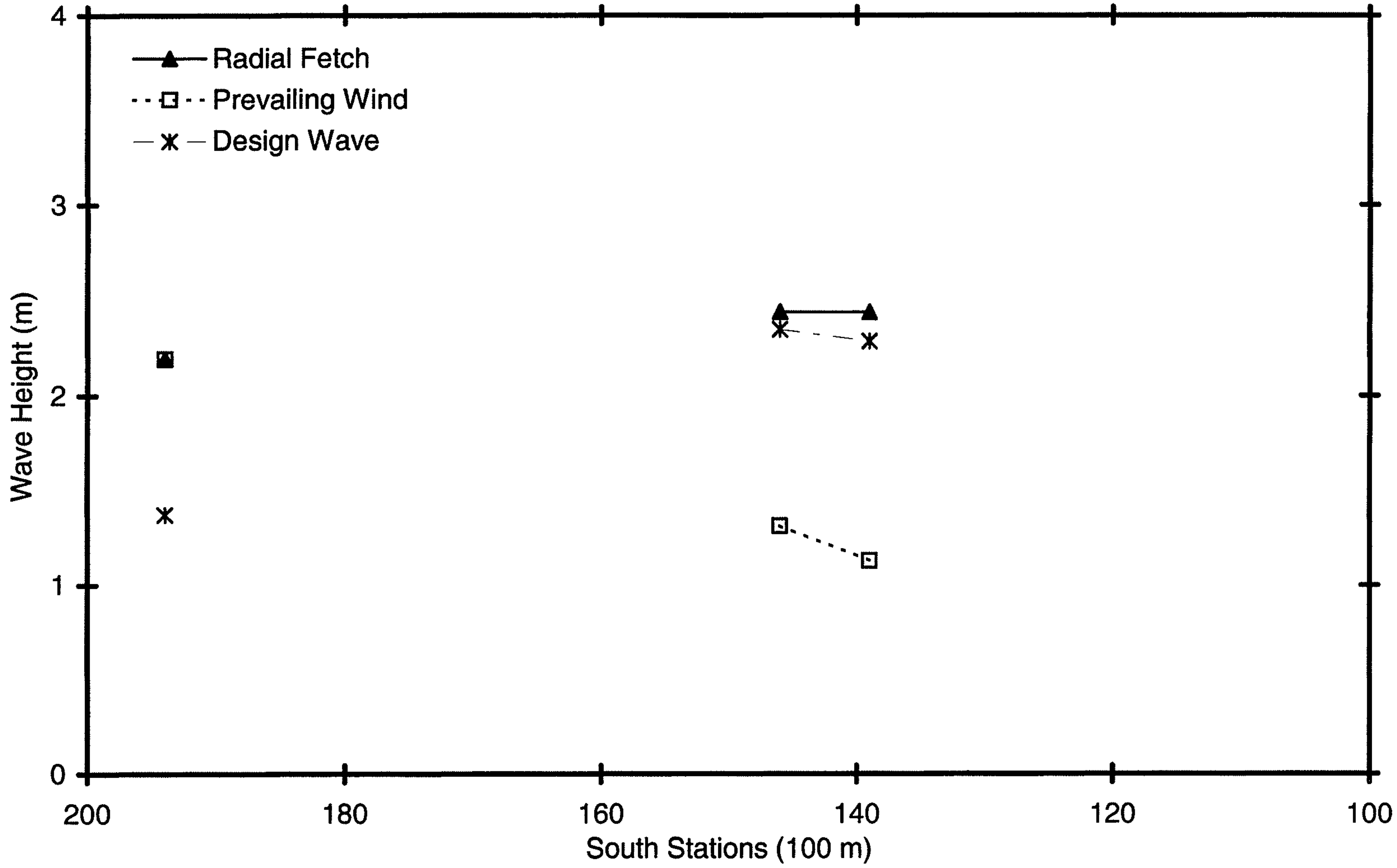

Figure 6.3.a Wave Heights, Dykes 3 and 4 South

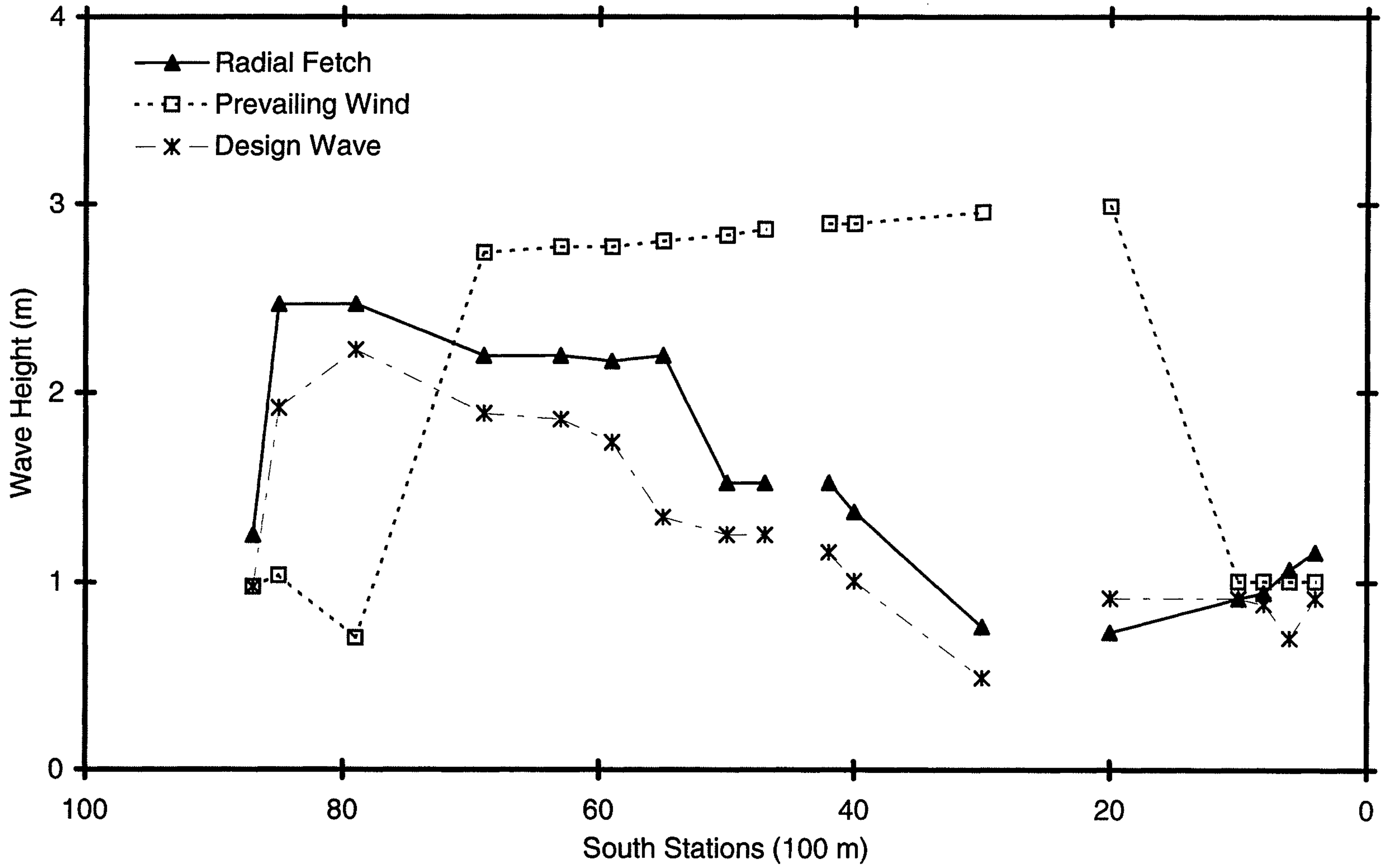

Figure 6.3.b Wave Heights, Dykes 1 and 2 South

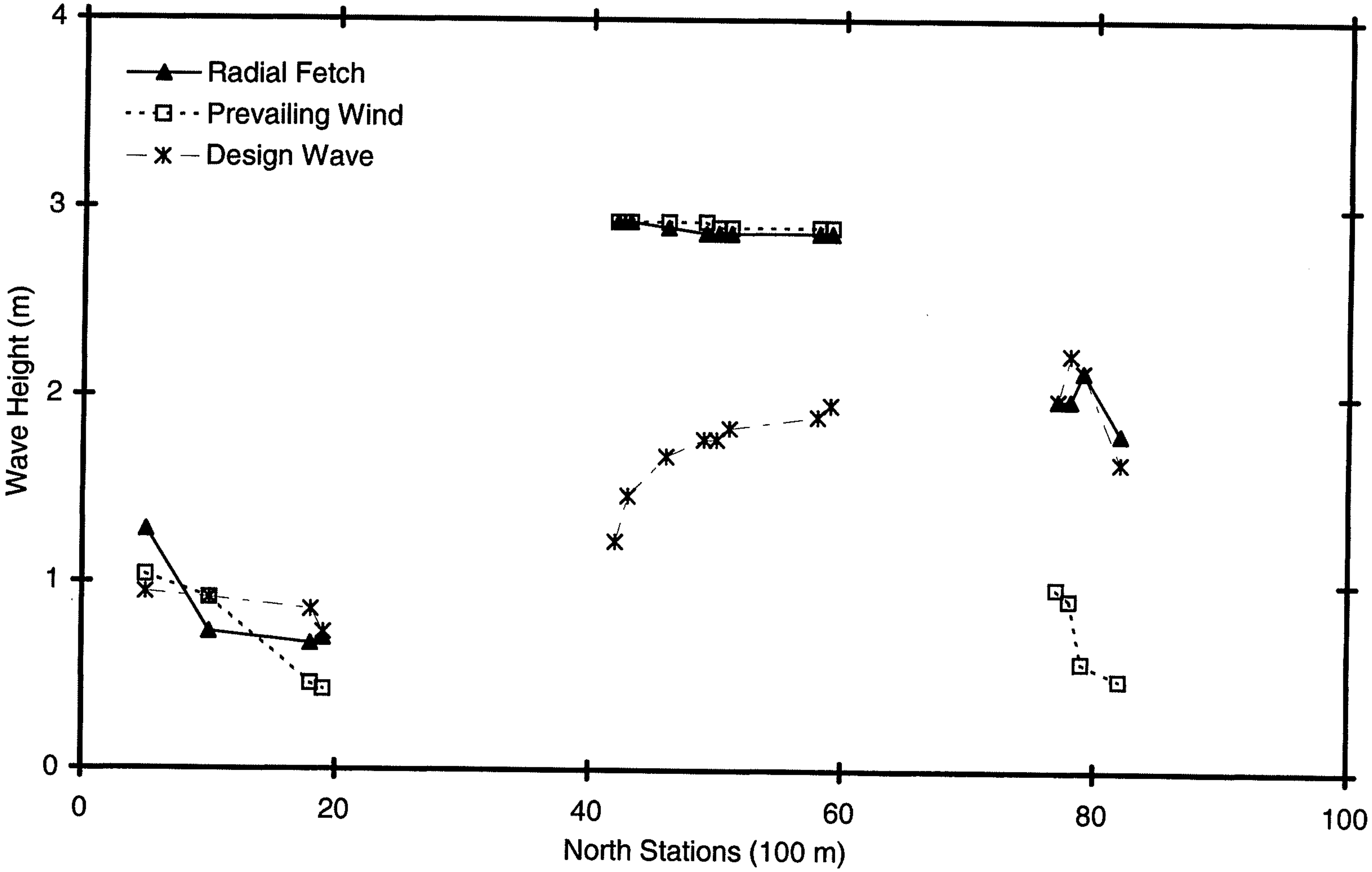

Figure 6.3.c Wave Heights, Dykes 1 and 2 North

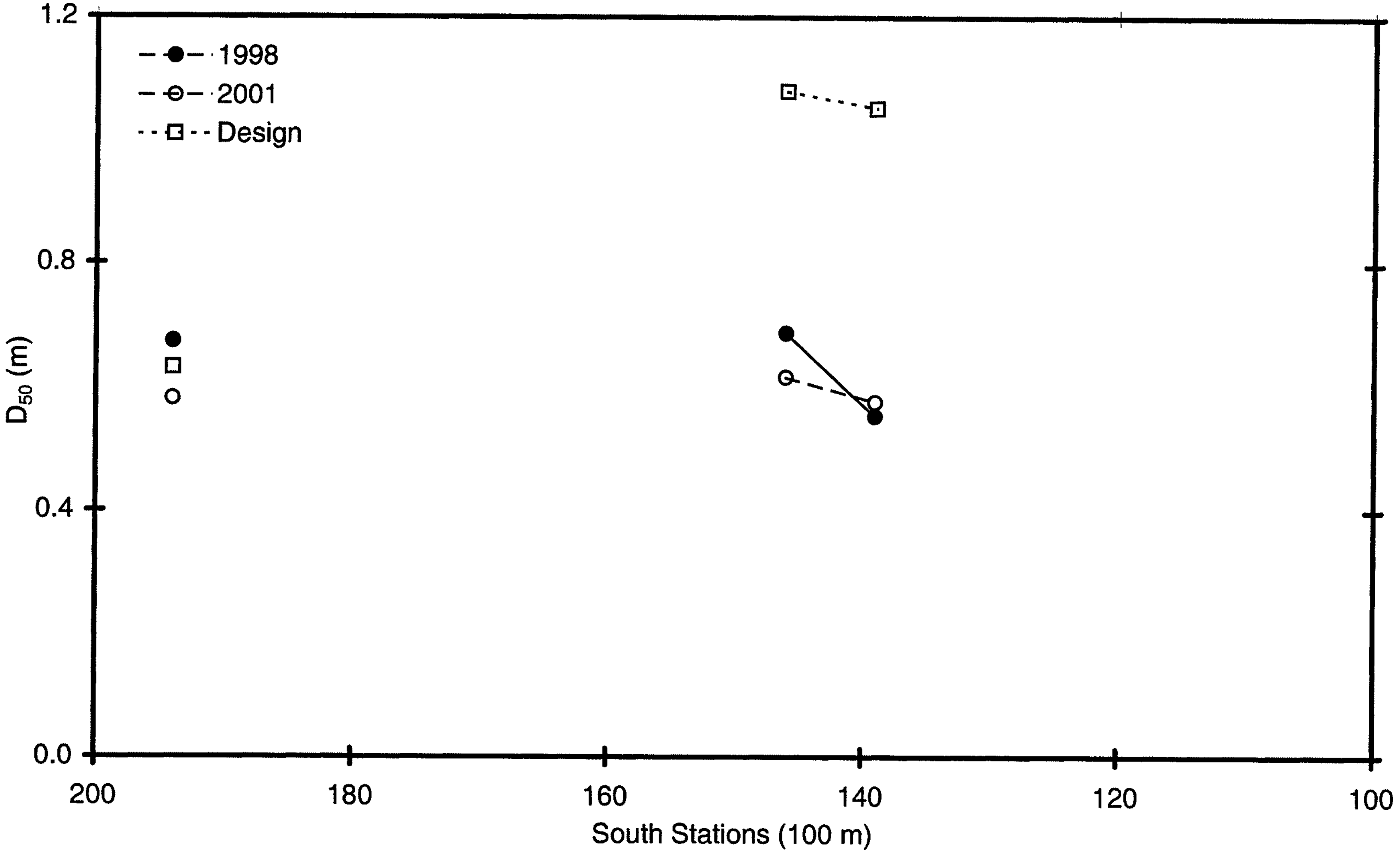

Figure 6.4.a D_{50}, Dykes 3 and 4 South

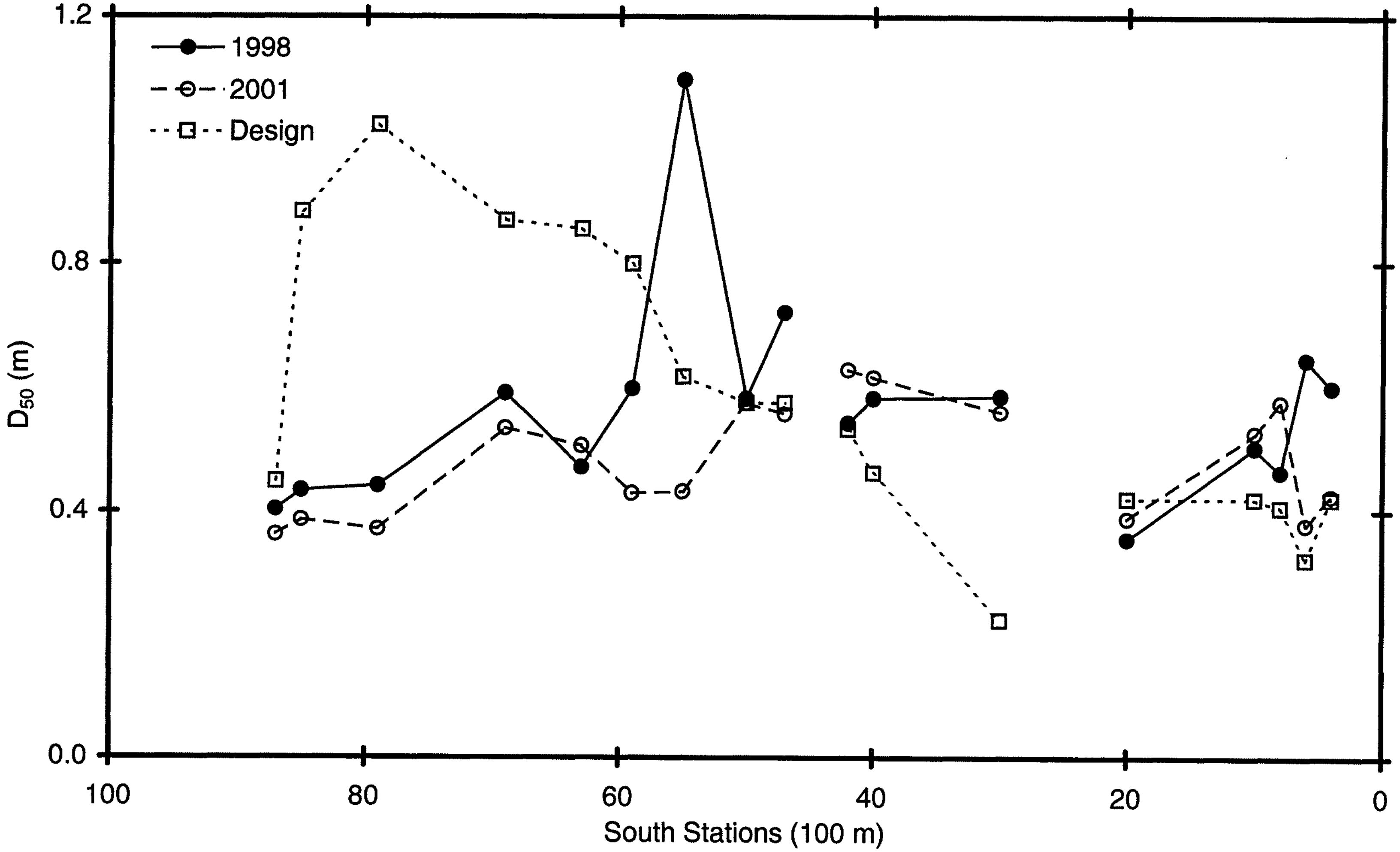

Figure 6.4.b D_{50}, Dykes 1 and 2 South

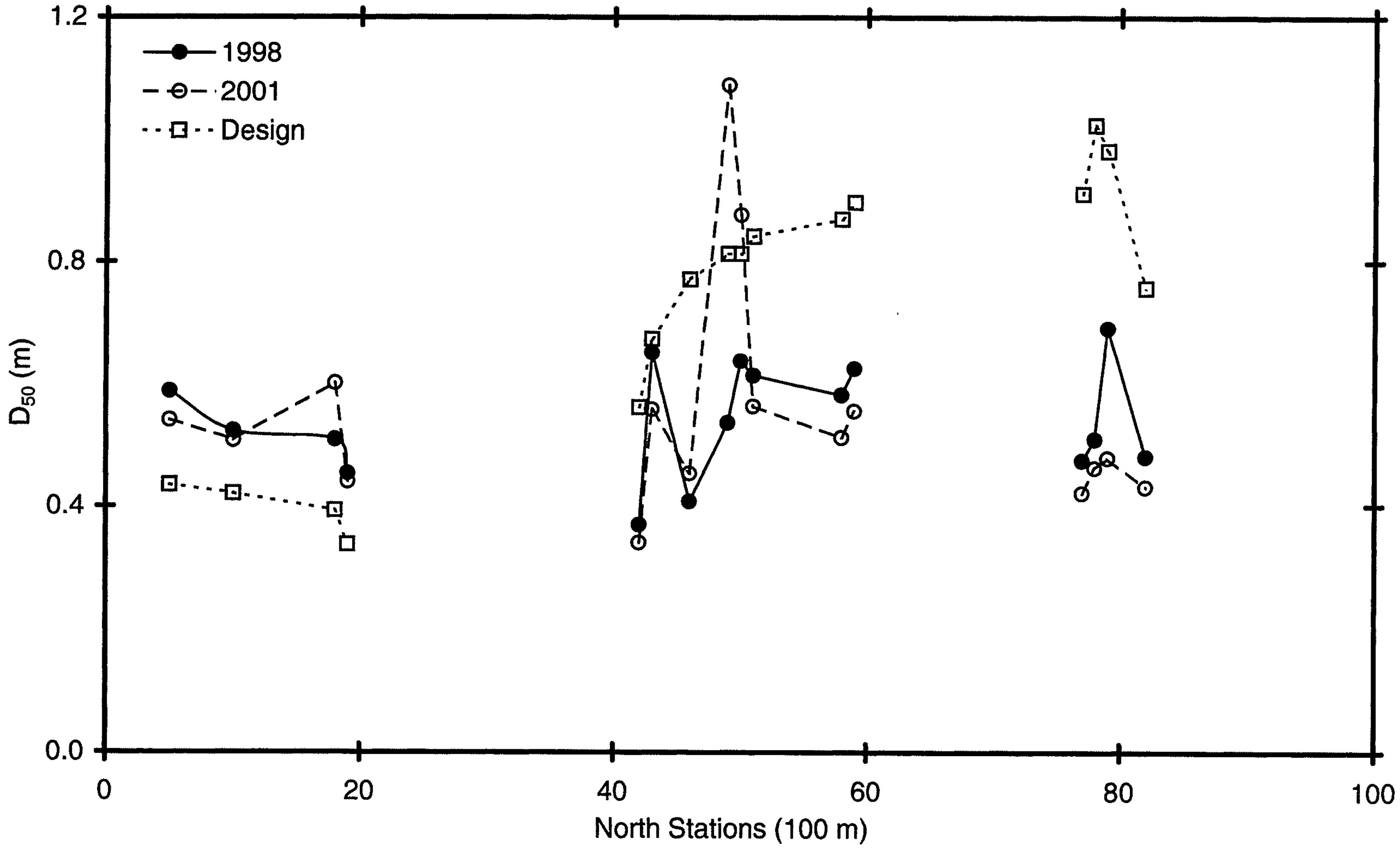

Figure 6.4.c D_{50}, Dykes 1 and 2 North

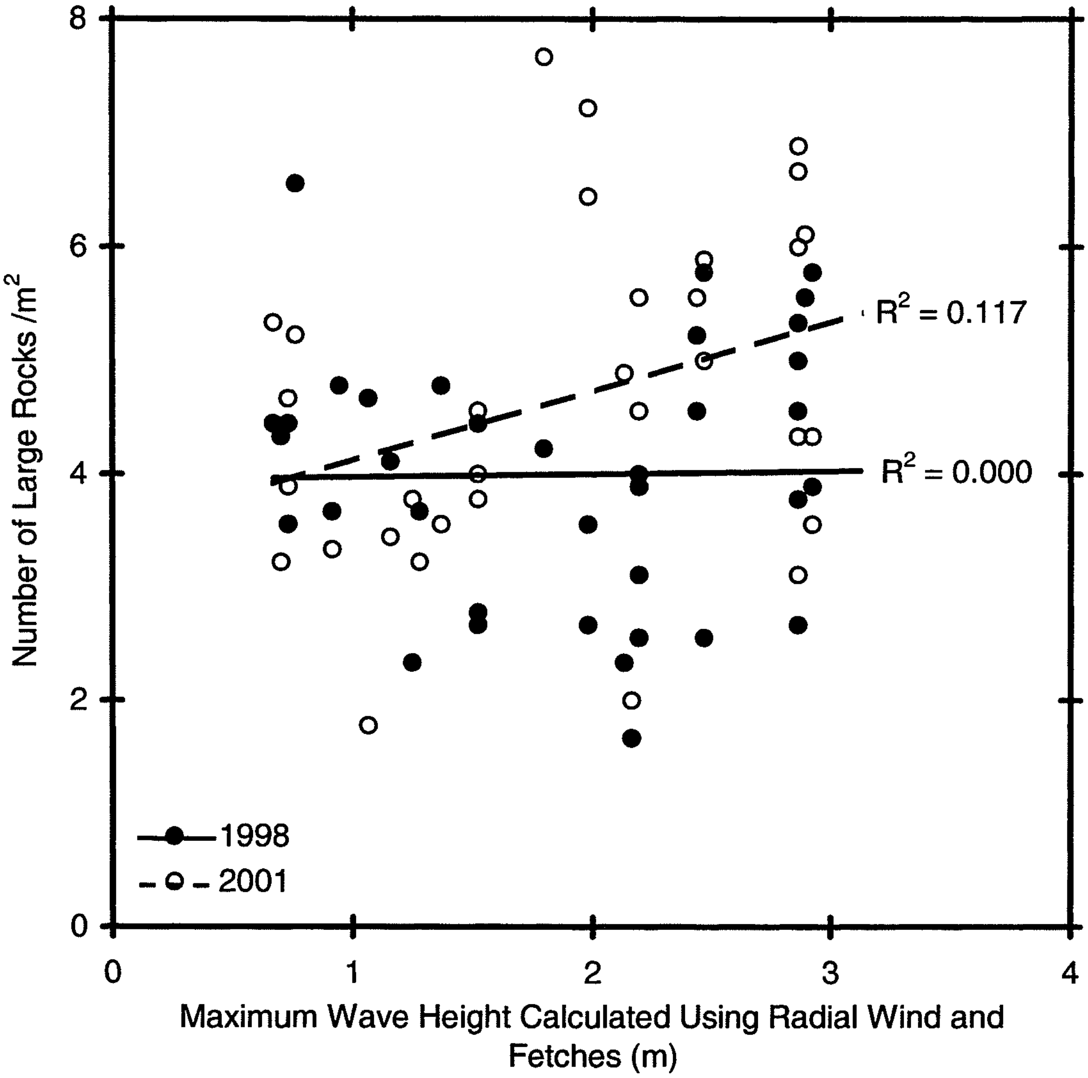

Figure 6.5 Wave Height Using Radial Wind and Fetch versus

Number of Large Rocks

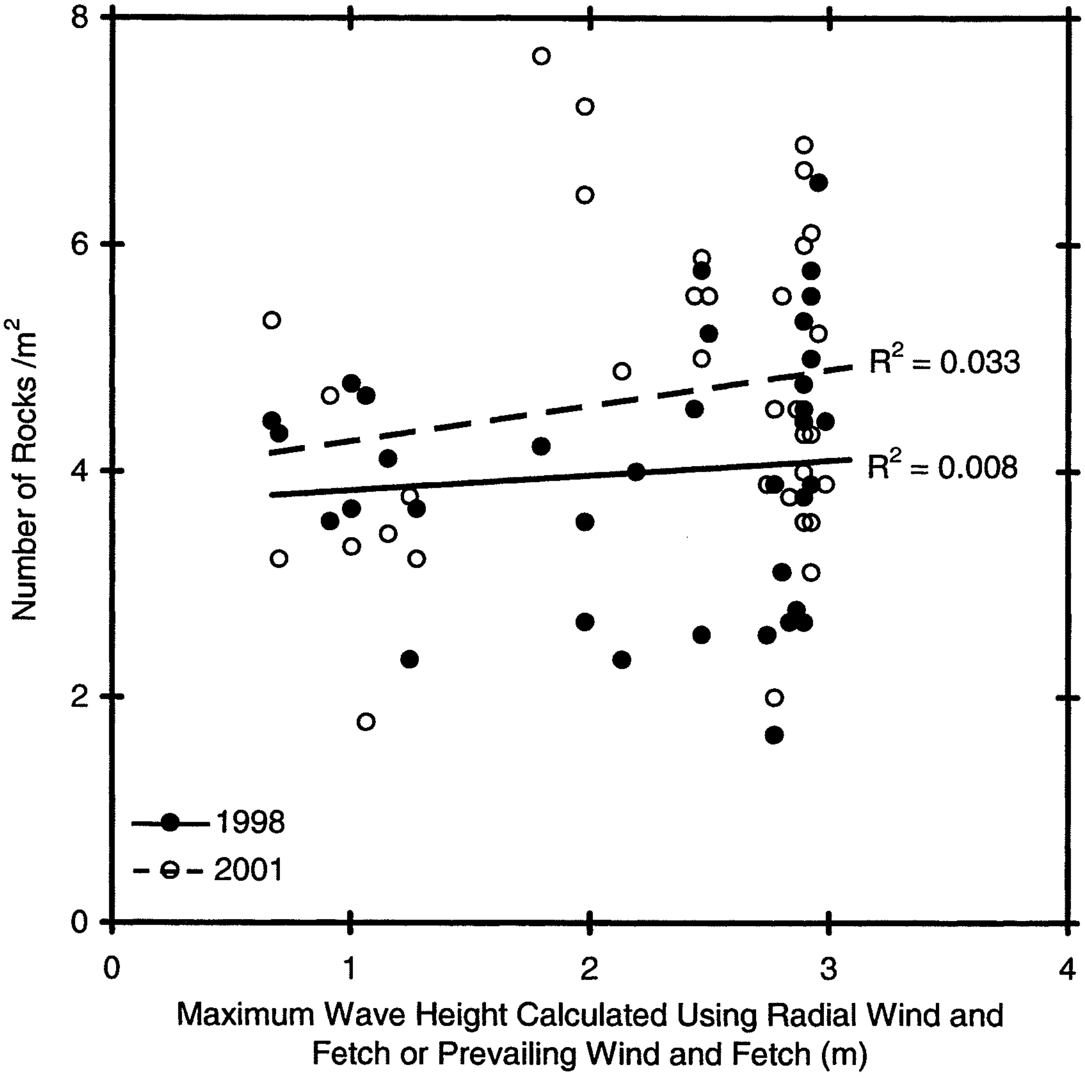

Figure 6.6 Wave Height Using Radial or Prevailing Wind and Fetch versus

Number of Large Rocks

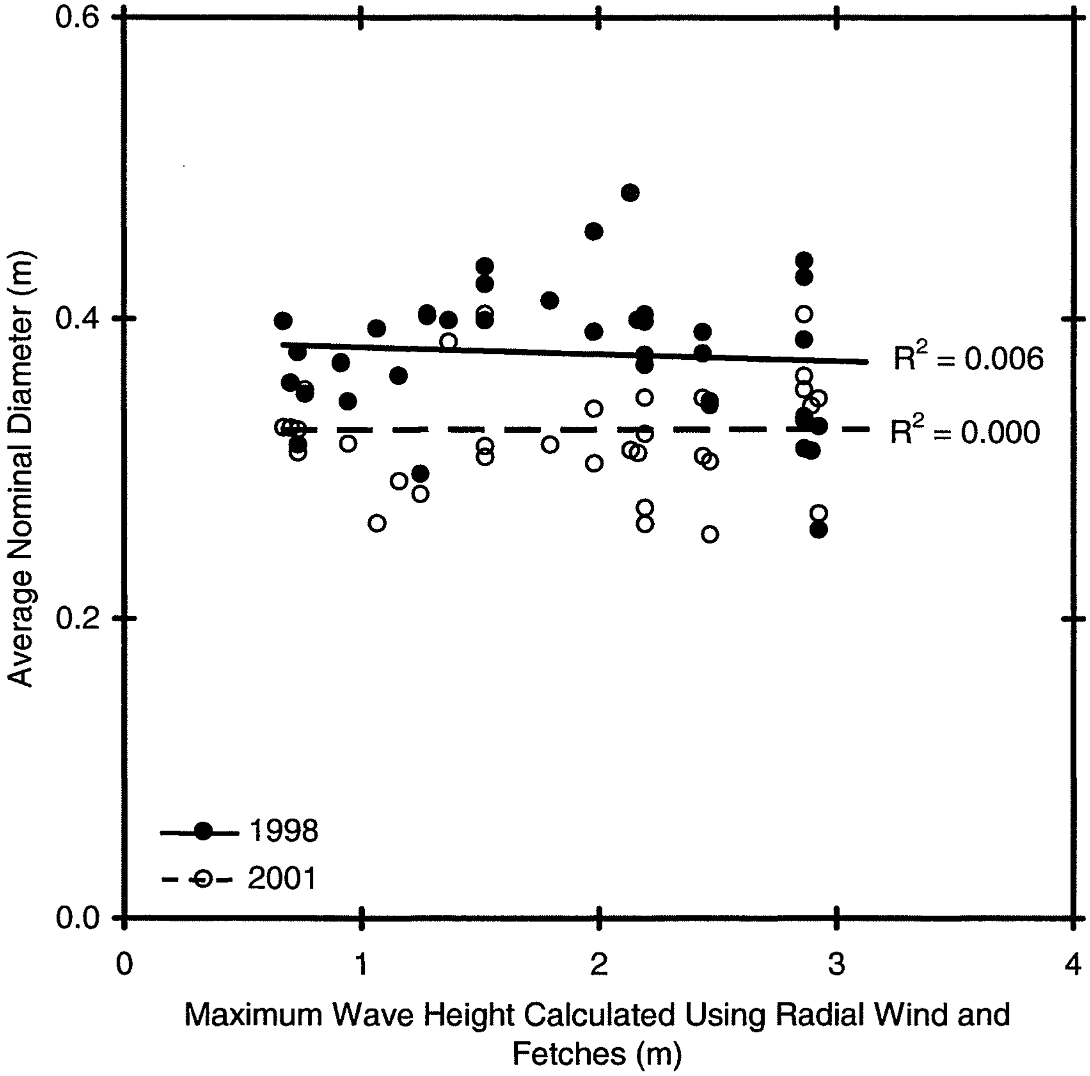

Figure 6.7 Wave Height Using Radial Wind and Fetch versus

Average Nominal Diameter

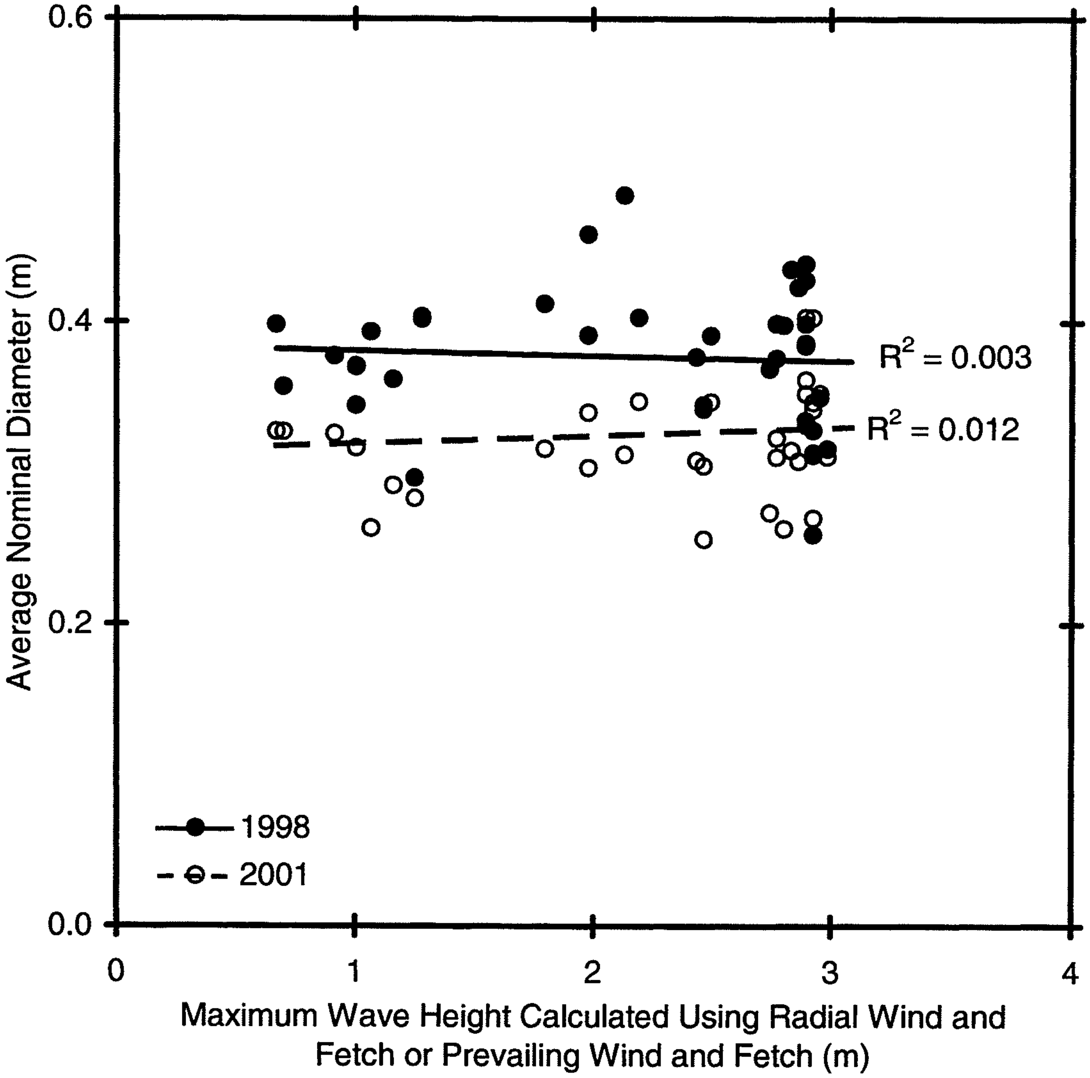

Figure 6.8 Wave Height Using Radial or Prevailing Wind and Fetch versus Average Nominal Diameter

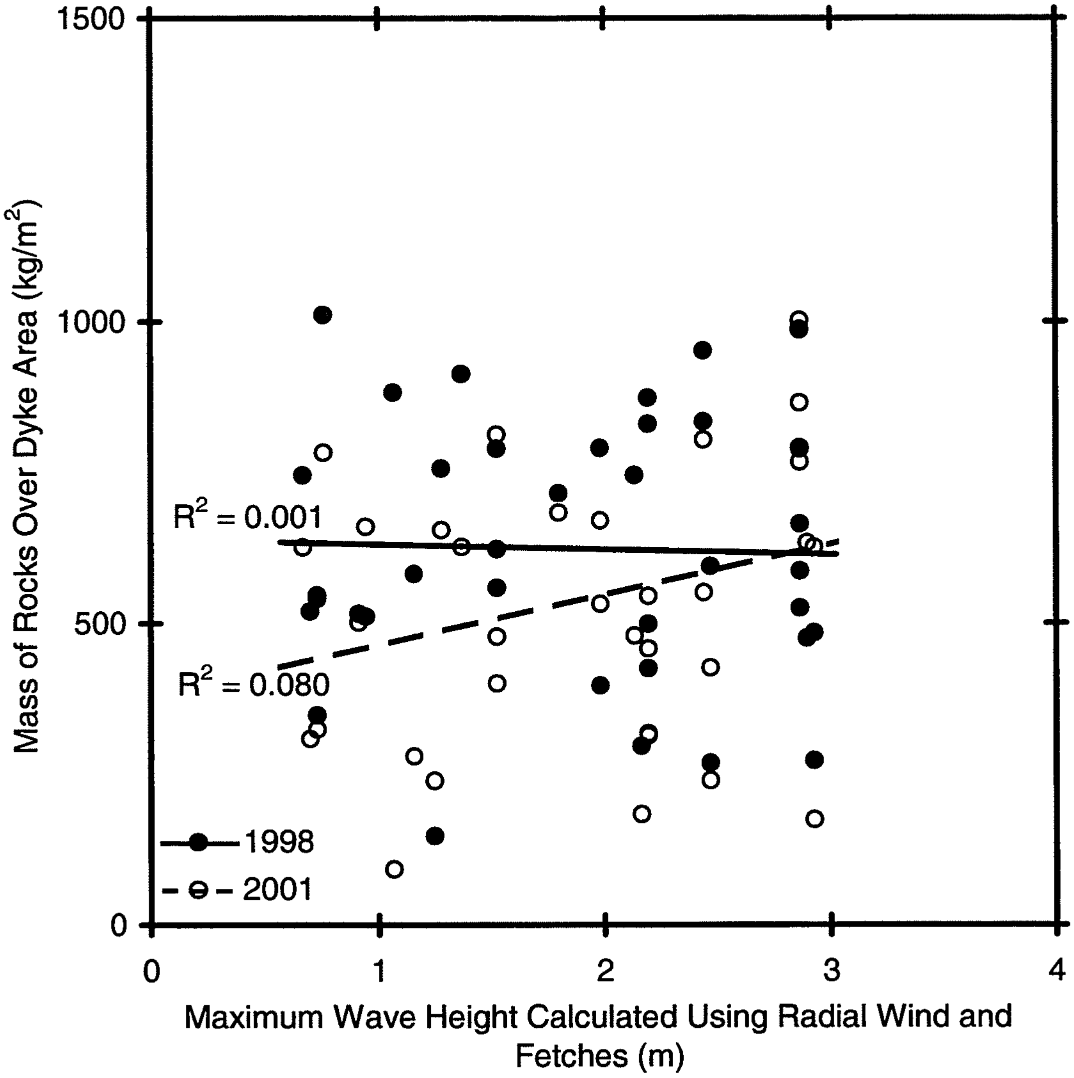

Figure 6.9 Wave Height Using Radial Wind and Fetch versus Mass

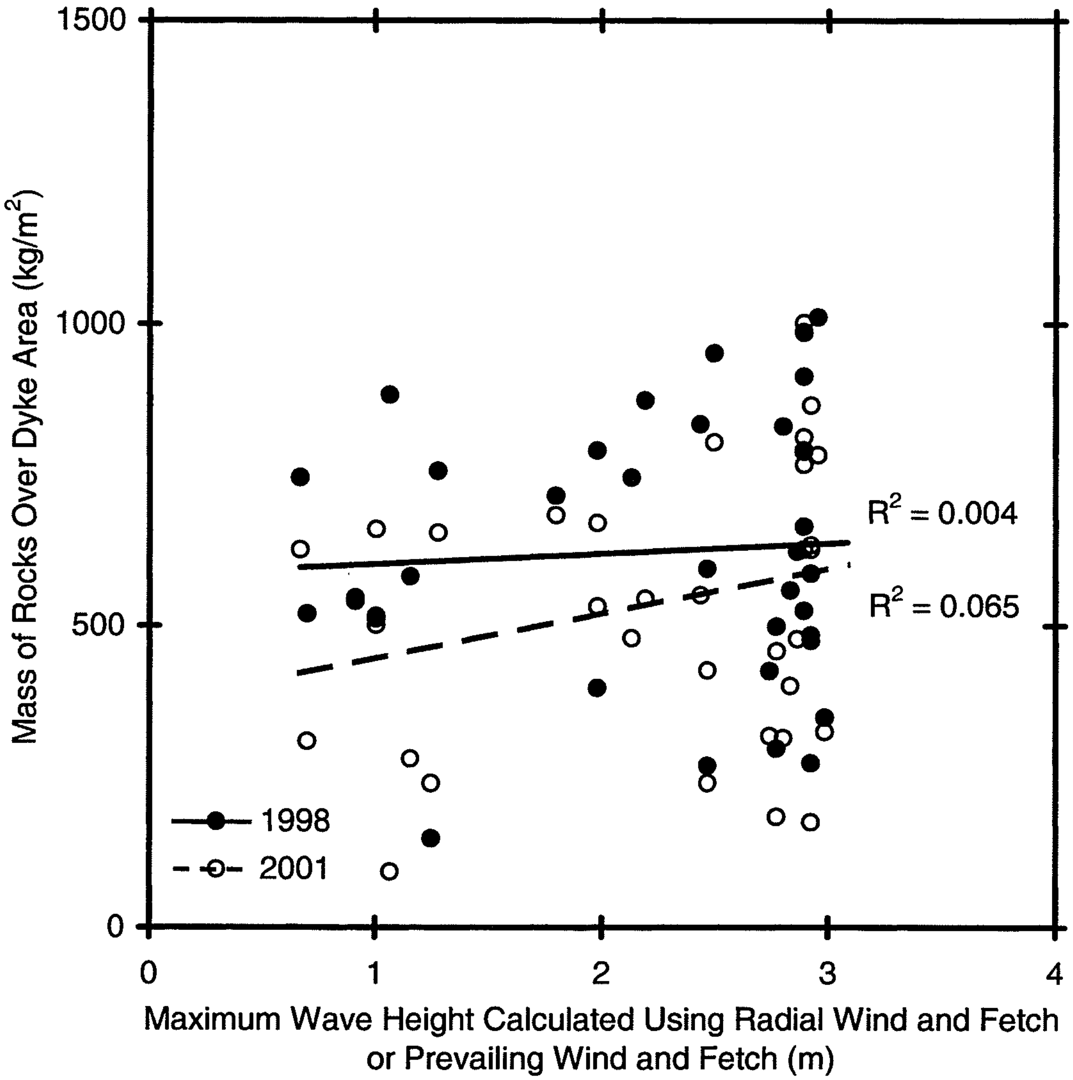

Figure 6.10 Wave Height Using Radial or Prevailing Wind and Fetch

versus Mass

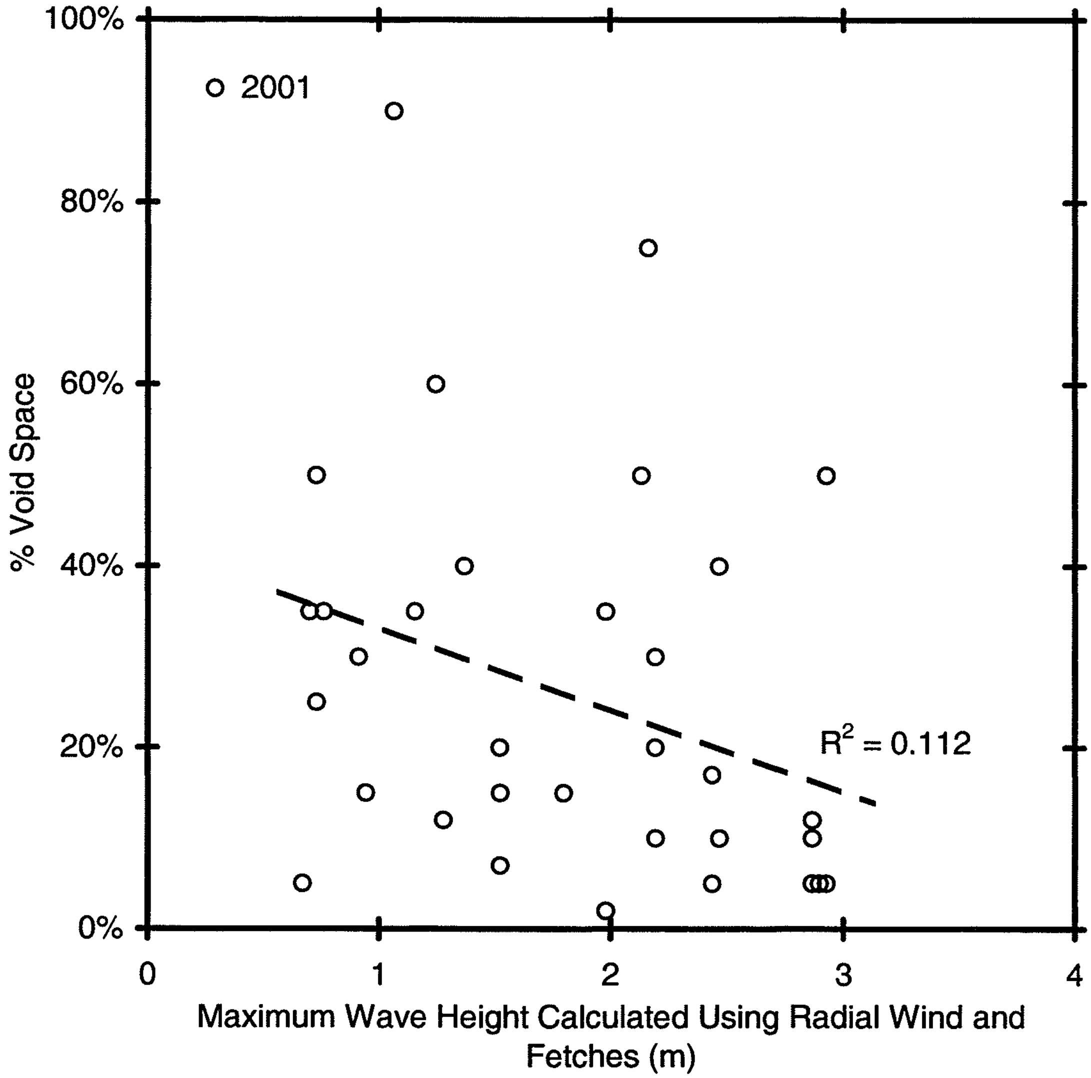

Figure 6.11 Wave Height Using Radial Wind and Fetch versus Voids

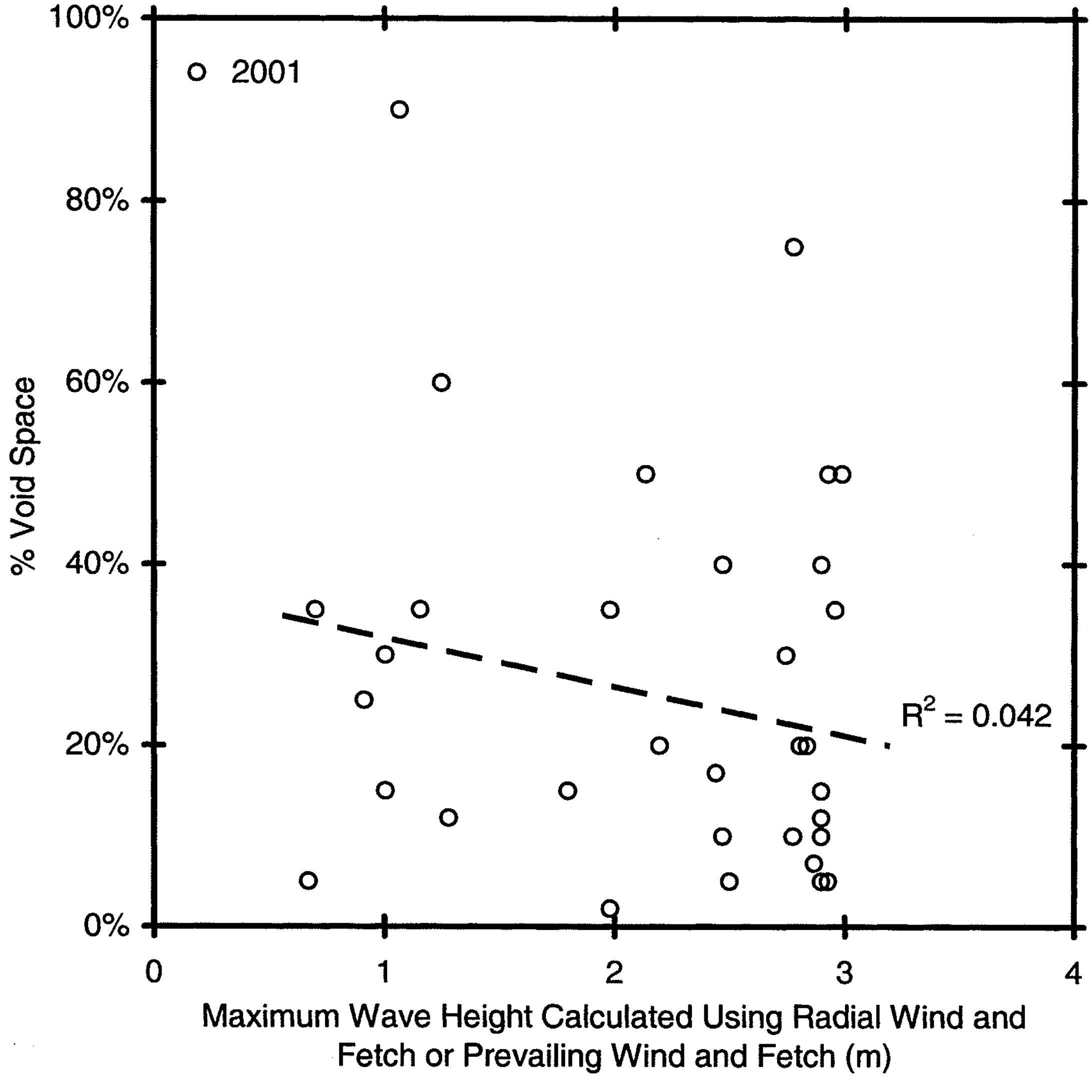

Figure 6.12 Wave Height Using Radial or Prevailing Wind and Fetch

versus Voids

Chapter 7: Discussion

7.1. Introduction

According to the field studies conducted during this research, the riprap at this site is disintegrating. The *capacity* of the riprap to protect the dykes from wave action in the long term depends on the type of limestone present, as well as the size and amount of that limestone. The *demand* on the riprap depends on the wind velocity, orientation, 'fetch' distance across the reservoir surface, and wave energies. This discussion examines the relationships between the demand placed on the riprap in terms of wave action and the capacity of the riprap to protect itself against the various processes that can lead to degradation.

7.2. Evaluation of Performance

Limestone as riprap is known to break down more quickly than more commonly used rocks such as granite. As discussed in Chapter 2, the limestone is porous and can be expected to break down, either by fragmenting or by surface spalling, especially in wet conditions. The limestone at the site studied in this project is also known to be irregularly bedded with clay or shale, which normally would mean it is even more susceptible to degradation when subject to wetting-drying and freezing-thawing processes. The action of wind-generated waves on the sides of the dykes allows water to wet the limestone, enter the pores and bedding layers, and cause surface spalling in summer and cracking when the rocks freeze in winter.

7.2.1 Amount of Riprap

As discussed in Chapter 4, evidence from the field work points toward a decrease in average nominal diameter and mean diameter D_{50}. As mentioned previously, this is not unexpected for this rock type but the field data now allow the rate of breakdown to quantified, however approximately. As reported by the owner, the original riprap had a minimum design D_{50} of 0.50 m, and obviously some of the riprap would have been placed with a somewhat higher D_{50}. The design value of 0.50 m is actually smaller than the average D_{50} of the riprap in 1998, which was 0.55 m. (These results are shown in Figures 4.14.a through c.) According to the field study in 2001, the size of the riprap then decreased to an average D_{50} of 0.51 m. These numbers are relatively consistent across the dyke system, though some sites have a D_{50} as low as 0.29 m and several sites as high as 1.10 m. As a general observation, the decrease in size does not appear related to the demand placed on the riprap by wave energy, but appears broadly consistent across the dyke system (Figures 6.4.a through c and 6.7). The reasons for the decrease in size are discussed more fully in Section 7.4.

Of more concern, is the observation that the size of riprap, at the time of the 2001 field study, did not appear to meet the design D_{50} at many locations and therefore may not have been large enough to resist the environmental demands placed on the riprap. Figures 6.4 a through c show that the design D_{50} varies significantly across the dyke system due to variations in design wave heights along the various sections of dyke. The design D_{50} varies from as low as 0.2 m to as high as 1.1 m in a few locations. Interestingly in some areas, the field measured D_{50} appears to follow the design values to some degree. As the design D_{50} increases and decreases, the measured D_{50} also increases and decreases. Whether this was arranged knowingly at the time of construction is un-knowable at this time. The replicating pattern of design D_{50} is not consistent across the dyke system. The measured D_{50} does not become as low as the lowest design D_{50} and more importantly it does not reach many of the highest design D_{50}'s in the areas of highest demand. During the life of the structure, and more recently since this project was started, the owner has increased the size of riprap placed during replacement programs in areas where greater amounts of degradation were observed. Riprap has not been replaced in areas with less degradation. This might explain why the average measured D_{50} is larger than that originally placed.

The field studies also identified an unexpected result that the number of 'large' rocks appears to increase with time (Figures 4.12.a through c). This can perhaps be attributed to differences in measurement methods, movement of rocks, or certain types of breakdown mechanisms.

If different measurement methods were used during the field seasons between 1998 and 2001, then the differences would be systematic and the increase in number of rocks would be consistent across the dyke system. In fact, the changes are not consistent. While many locations show an increasing number of large rocks with time, other locations have the same number or a smaller number or rocks (Figures 4.12.a through c).

Another check for inconsistencies due to changing field methods is to check the total mass of large rock in the measurement sections. There is one area of about 2 km in length where the mass of large rocks appears to have increased (Figures 4.15.a through c). The difference is relatively small, less than 100 kg, but visible in Figure 4.15c. Looking once more at Figure 4.12.c, the numbers of large rocks in this area has generally increased from 1998 to 2001, but there are some sites with a lower number of rocks. Figure 4.13.c indicates a general increase in average nominal diameter from 1998 to 2001 in the same areas where the number of large rocks has increased. In another area, there is a decrease in average nominal diameter and in number large rocks, yet the increase in mass appears consistent across this area. These results appear to indicate no systematic differences in measuring techniques over the period of four years of fieldwork. The conclusion can be drawn that rocks are either breaking down into two pieces that still satisfy the criterion for 'large rocks', or else they are being moved by ice action that plucks them or rolls them down the dyke face.

Reasons for the observed increases in the number of rocks and decreases in their average nominal diameter and mass are discussed in Section 7.4.

7.2.2 Beaching

It was expected that this study would capture evidence of beaching, which was noted visually by the owner's engineers and by the author. Beaching would imply more aggressive breakdown of the riprap and more significant reductions in the available level of protection. While conducting the field studies, evidence of beaching was visible and photographed as seen in the photograph included as Figure 4.19. At the time of each of the field studies in three separate years, the forebay level was too high to measure the sizes of the rocks in the area of the beaching. The forebay levels change from year to year, depending on the conditions within the watershed area and on how the owner is regulating the water level for optimum power generation. According to an unpublished forebay water level graph, from the owner, very generally, the water level is at its lowest levels in March through April, then reaches its peak levels in September through October. In July it is generally relatively close to the peak level. The significance of this observation is that there may be regions of beaching at lower elevations than could be examined in this study. If beaching is present, the level of protection will be below recommended design values.

7.2.3 Digital Analysis of Photographs by Computer

Digital analysis of photographic images was considered as a possible alternative to physically measuring the riprap on the dykes. As a result of some preliminary study, the method has some limitations that must be overcome to make it work effectively. Further work seems likely to make this method an attractive method for future research. First, it is important to get good quality photographs that include an appropriate scaling marker and are at an angle that permits appropriate measurement.

The objective of the rock counts that form an important feature of this work will be to measure the size of rock on the side slopes of the dykes. For this, it will be helpful to have photographs taken perpendicular to the slope surface, for example by a helicopter. Meanwhile, however, the photographs taken during this study were taken either from the dyke face itself or from a boat (at water level). Both of these sets of photographs were taken at too great an angle to the slope surface for accurate measuring results. Not only are many of the rocks obscured from view, but the sharp angle means that height and depth are distorted in the photograph.

The owner made helicopter video footage available, but it contains no scale with which to size the rocks. There is also a problem with resolution when capturing still photographs from video footage. Individual rocks, particularly the smaller rocks, are difficult to identify at lower resolutions.

To accomplish the correct angle with an appropriate scale, still photographs could be taken from either a truck crane with a long boom or from a helicopter. It is important that each photograph contain a suitable scaling target. Photographs like this could be done relatively quickly and economically, probably more quickly, reliably and cheaply than by direct measurement.

The second limitation is the difficulty of actually identifying individual rocks within photographs. Several different computer-imaging programs were briefly examined, but none of them performed as desired. In order for the computer to be able to identify individual rocks, the colours of the rocks must be significantly different from the background. In this application, the colour of the rocks is too similar to the background and the computer interprets shadows, unlit openings and bright spots as individual rocks.

Another possibility is to draw a line by hand around each individual rock visible in the photograph. This is tedious and time consuming for the analyst. After combining this time with the time and effort needed to take the photographs, there may in the end be only limited savings in time and expense.

Lastly, the rocks must be measured. The programs that were investigated are able to measure individual rocks, but only if they have been properly identified and isolated. Another possible method would use AutoCAD and its scaling abilities. In this case, the individual using the program could identify the rocks and measure them.

One benefit to photographic measurement would be an accurate measurement of surface area, particularly the evaluation of the percent of void space. The current approach is quite subjective.

Using photographic images promises some advantages but the method requires thorough testing to determine if the diameters found correlate to those measured in the field and whether accurate volumes can be determined.

7.3. Capacity of Limestone

As previously mentioned (Chapter 5), the limestone in this project is less susceptible to degradation by wetting and drying, and freezing and thawing than was previously expected. It lost virtually no mass in wetting-drying tests and most of the samples performed very well in freezing-thawing tests, as discussed in Chapter 5. Only some showed high rates of degradation. There were three main grouping of limestone samples based on geological properties. Those in one group performed well, those in the second group performed reasonably well, while those in the third group all performed poorly. There was also a small fourth group of granite samples. These groups will be discussed in the following paragraphs.

The acceptability of riprap is generally decided based on its capacity to pass a number of laboratory tests. The acceptance criteria recommended by Acres (1988) for riprap in northern climates (presented in Chapter 2) have been used here as the criteria for this project. As discussed in Chapter 5, the laboratory tests conducted consisted of Absorption, Bulk Specific Gravity, Wetting-drying, Freezing-thawing, and Iowa Pore Index test. Acres does not include the Iowa Pore Index test in their paper, and it will be discussed in later paragraphs.

The riprap tested in this program has been grouped into four classes on the basis of geological properties. The classes were (1) clastic limestone, (2) off-white or tan limestone, (3) limestone with red or brown beds and (4) granite. Conveniently, samples within each of these classes generally performed very similarly in laboratory tests. Discussions will therefore revolve around these groupings, rather than individual samples.

Many of the limestone samples preformed in an unexpected manner. All of the clastic limestone samples (class 1, in the previous listing) fail the Acres (1988) acceptance criteria for specific gravity (≥ 2.6) and absorption (≤ 2.0%) (Figures 5.1 through 5.3). However, they pass the freezing-thawing criterion even after the tests had been run for extended periods as described in Chapter 5. Meanwhile, all of the samples of limestone with red or brown beds (class 3) pass the acceptance criteria for specific gravity and absorption, yet fail the freezing-thawing tests. As discussed in Chapter 2, the rationale for the specific gravity tests and absorption tests is to identify samples that will absorb enough moisture to cause failures in freezing-thawing tests. The tests conducted for this research suggest the correlation between specific gravity, absorption and freezing-thawing resistance is at best weak.

The off-white or tan limestone samples (class 2) did not behave consistently as a group. Some samples passed and some failed according to the Acres (1988) acceptance criteria for each of the tests. The small number of granite samples (class 4) all performed well.

These tests show that there are certain types of limestone that are able to withstand the freezing-thawing demands placed on them. These groupings were not identified until after the field studies. As a result, the descriptions taken in the field studies were not fully able to correlate to these geological groupings of the limestone.

The groupings identified by geological examination most likely relate to specific beds of limestone material, since the rocks in each grouping have roughly the same geological and physical properties. Accordingly, these bedding layers are likely found at approximately the same elevation, across the area. Assuming each quarry was excavated in parallel benches to approximately the same elevation, the riprap across the dyke system are likely composed of similar material from the same bedding layers, even when they are taken from a different pit. As a result, there will be some statistical variation of material across the dyke system, but in general the riprap should be distributed with approximately the same proportions.

Since the limestone that was used in the testing program had been removed from the dyke face, it is possible that they represented only the more durable limestone available in the quarry. Perhaps the less durable limestone riprap has already deteriorated beyond the size of what can be tested. If more local limestone were to be used in future, the challenge will be to identify more durable limestone beds in the quarries and avoid less durable limestone.

Determining whether the limestone remaining in the quarries has acceptable durability will require opening the quarries, testing each layer of material, and then comparing the results of the new tests with those found from samples taken from the dykes. If this is done, it will be important to remember that the dyke samples may represent only layers that are more durable, and that other material originating from specific layers of the quarries may have already disintegrated.

To determine the capacity of each of the different types of rock, individual limestone layers could be tested to verify if that layer has appropriate physical properties for use on the dykes. Considering the length of time that is required for most of the laboratory tests, this becomes a very time consuming and costly process. If, however, the time and expense is acceptable, then carefully selected local limestone layers with appropriate physical properties could be used to replace disintegrated rock on the dyke face.

Evaluation of the rock can be greatly enhanced by the use of the Iowa Pore Index test. The Iowa Pore Index Test correctly identified each of the samples that performed poorly in freezing and thawing. It also produced consistent results that showed groups of samples with similar geological properties performing similarly in Iowa Pore Index Tests. This test reduces the amount of time taken to test rock to only 30 minutes per test and can be done in a small site laboratory. Individual limestone layers could be tested relatively quickly during excavation and if appropriate, used as riprap.

7.4. Relationship of Demand to Degradation Processes

As discussed in Chapter 6, there is some systematic evidence of wave heights being related to measured degradation of the riprap. However, the relationship does not appear consistent at all locations along the dykes. Early in the project, it was expected that the demand from storm waves would to be reflected in the data collected from the rock counts on the dykes. Higher energy demands were expected to correlate with lower numbers of riprap, smaller diameters, or smaller masses in the areas of greater demand. By relating the information found in field studies directly to wave heights, some relatively weakly expressed relationships appear to arise. These relationships may indicate specific types of degradation processes at work.

As a generalization, Figure 6.9 indicates that rock mass per unit area decreases most over the period of the study in areas with smaller waves heights. Figure 6.7 indicates that decreases in average nominal diameter appear to be equal everywhere along the dykes and independent of the wave heights. Meanwhile Figure 6.5 indicates that the number of rocks appears to increase in areas where wave heights are large, and to be unchanged in areas of smaller wave heights. These variations between the areas with larger or smaller wave heights may indicate different types of mechanisms for degradation.

In areas with smaller wave heights, the main mechanism for degradation may be spalling, since the average nominal diameter and mass are both decreasing in these areas. A number of the samples tested in freezing-thawing tests were seen to spall and lose mass during the tests discussed in Chapter 5. The freezing and thawing tests also indicated that some rocks have the potential to shatter completely into small pieces, which would mean a decrease in the number of 'large' rocks.

The number of rocks remaining also creates questions about what is happening with the smallest of the large rocks. These should degrade as well and a number of them would no longer be large enough to include in this study. The smallest of the large rocks either must not lose very much or perhaps larger rocks break off pieces large enough to be counted as a large rock. Both of these mechanisms may be occurring to some degree, considering the average nominal diameter decreases by an average of 0.05 m.

In areas where waves heights are large, the main mechanism for breakdown may be very large rocks breaking down into two or more large rocks. This means that the mass may not change significantly since the two "new" rocks are still included in the study. In this case, the number of rocks will increase, as is visible in Figure 6.5. This may mean that while the rocks in this area are degrading by spalling or shattering, these are not the main mechanisms occurring in the areas with larger wave heights. It will be understood that producing two 'large' rocks from one larger rock does not improve resistance against wave action.

The difference between the mechanisms may be related to the wave heights when wetting produced by waves generated during wind events is followed by freezing temperatures, during the fall and spring. In areas where wave heights are small, the rocks above the water level at freeze-up may only be surface saturated, while those in areas with larger wave heights are repeatedly wetted and may be more completely saturated. As well, a larger proportion of the riprap will be wetted in areas of larger waves.

The water level is at approximately the same elevation in all areas, generally, at its highest in fall and lowest in spring. It is during these times that the freezing-thawing potential is the greatest, when wind events tend to be stronger, waves may wet large areas of riprap, and air temperatures may drop below freezing. In the fall, with high forebay levels, it may be that most of the lower measurement grids are below the water level and are not affected by cyclic freezing and thawing. Meanwhile, in the spring, the measurement grids at mid-height on the dykes may be high enough above the water level that they are not wetted up during storm events, while the lower grids are. The fact that different elevations of the dyke face are exposed during the spring and fall seasons may explain why there was no difference in the correlation between location and breakdown when the grids were examined in terms of their elevation on the lower, middle and upper parts of the dykes.

7.5. Other Possible Mechanisms of Degradation

Other possible mechanisms for riprap degradation include shifting or plucking of rocks by ice, and rocks being rolled by wave action. These mechanisms would change the measurements of the riprap, but are considerably less predictable than freezing-thawing degradation. They are not included in the scope of this project. As discussed in Chapter 2, plucking by ice should not be able to pick up the largest of the rocks on the dykes. Similarly, wave action alone should not be able to move the largest rocks. As a result of these mechanisms, a reduction in the number of rocks could be expected, but the average nominal diameter may actually increase as the larger rocks are left behind. These ideas are brought up for discussion or future work, but were not studied in this report.

7.6. Geographic Information Systems

A GIS database would be useful for managing the riprap and wave information. It could be used for monitoring the riprap over a period of time, keeping track of various replacement programs and determining if a rate of degradation can be established for specific areas of the dykes. Some work was done towards building a GIS database in a program called Arcview. Because it was clearly site specific, and the owner has asked for the site location to be kept confidential, the work on developing a GIS database could not be included in this report.

7.7. Conclusion: Effective Management

There are a number of improvements for future similar research at this and other similar sites. Visual surveys, wind and wave analysis could be completed before the field studies in order to identify locations of specific interest for riprap measurement, in addition to the grids at regular intervals. Laboratory testing and geological descriptions of riprap samples could be completed prior to field studies, so rocks can be better identified in the field and correlated with the laboratory results. If budget constraints allowed, samples could be taken for standard laboratory testing and/or Iowa Pore Index testing at selected intervals across the dykes, to verify whether the properties are consistent across the dyke system. The field studies could also be timed to occur at the lowest possible reservoir level, in order to collect data in the areas where beaching was visually observed.

This research is only able to speculate on the mechanism of deterioration of the riprap. Further studies into the possible mechanisms could also be completed to determine the reason for the apparent increase in number of large rocks, while the size decreased. Further studies on limestone, specifically as riprap, may determine conclusively whether distinct types of limestone are durable enough to be used as riprap with the same confidence as more common rock types used as riprap, such as granite. Further studies are also required to prove conclusively that the Iowa Pore Index Test can accurately identify durable rocks for use as riprap from the non-durable.

Potential Effective Management practices include using a GIS database to monitor and manage the riprap, using the Iowa Pore Index to determine durability of the riprap, and possibly changing the field study practices to include numerical imaging techniques.

Chapter 8: Conclusions and Further Work

The riprap at this site is breaking down at a rate that is challenging its capacity to provide adequate protection. It has reached a point where work is required over the next few years to upgrade the protection of the dykes. It is anticipated that replacement of the riprap will be done on a sequential basis over a number of construction seasons, so this research was aimed at determining if specific areas are experiencing greater rates of degradation. During a replacement program, the reliability of the dyke structures must be maintained, so significant quantities of riprap cannot be removed for testing.

This research uses simple linear regression and did not investigate alternative statistical methods. As previously mentioned the variable nature of the data produces especially low correlation factors and in some cases, negative R^2 values. Although these values are very low, the trends in the data and systematic relationships were considered significant. . One of the examiners has pointed out that further work into non-parametric statistics may find better statistical methods for natural systems and small sample sizes such as those appearing in this study.

Much of the limestone rock at this site meets the freezing-thawing criteria set by Acres (1988) and is acceptable for use as riprap. There may be rock left in the quarries which is satisfactory for riprap. The specific gravity and absorption criteria do not seem to adequately predict the durability of the limestone during freezing-thawing or wetting-drying cycles. They are therefore of limited value as predictors of rock quality in this application. The geological descriptions appear to correspond well to the durability of certain types of limestone riprap and can be used to characterize the riprap during future field studies.

The small number of granite samples demonstrated much higher resistance to freezing-thawing effects than the limestone. No supplies of granite riprap are available close to the dykes in this study. As in the original design, a balance must be drawn between performance, construction cost, and maintenance cost.

Because of its quick turn-around time and its ability to determine which rocks are susceptible to freezing-thawing degradation, the Iowa Pore Index Test is useful for quickly identifying good quality limestone both on the dyke system and in the quarries.

The precise processes causing the degradation are still unclear, though a series of possibilities clearly exist. Because more pieces of riprap were measured at many sites in 2001 than in 1998, the author suggests that initially ‘large’ rocks may be breaking up into two or more pieces that can still be classified as ‘large’. In some areas, the deterioration was evident and the rock numbers remained the same or decreased. This has been taken to imply typical degradation processes where the riprap is deteriorating slowly.

Some of the laboratory samples showed considerable tendencies to deteriorate, fragment, or indeed, shatter. However many of the laboratory tests showed that the rock had a larger capacity to protect against freezing-thawing and wetting-drying damage than previously thought. More field and laboratory study is required to determine whether these indications of good performance simply indicate that poorer quality limestone has already disintegrated.

In many places along the dykes, comparison of measured riprap sizes with sizes required by currently accepted design practices showed that the size and amount of the current limestone riprap was not adequate at the time of the field studies. The owner has been, and is being, proactive in completing repairs and replacement programs.

In many cases, the limestone riprap was shown to have adequate capacity to protect the dykes from environmental factors, such as wave action and damage by freezing-thawing and wetting-drying cycles. The demand on the riprap (related to wave heights in storm events) was not observed to have an effect on the diameter of the riprap. It did however appear to influence areas where the riprap is breaking up into pieces large enough to be included in the study. Further studies are required to determine conclusively the mechanisms of deterioration and to further develop the relationship between the capacity of the riprap and the environmental demands, in order to predict the timing and location of future riprap replacement programs.

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Appendix A: Further Information on the Iowa Pore Index Test

The Iowa Pore Index Test is a relatively quick and effective test, which was developed by the Iowa Department of Transportation to predict the ability of concrete aggregates to resist damage arising from freezing-thawing cycles. The test measures the amount of water taken up by a sample of aggregate in a specified amount of time. It has been was found to predict reliably the durability of the rock in freezing and thawing conditions.

The Iowa Department of Transportation began investigating tests to replace conventional freezing-thawing tests when they found that in some cases, concrete made using limestone aggregates performed well in freezing-thawing tests, but was susceptible to "D-cracking" (IDOT 1980). The term "D-cracking" refers to the deterioration of concrete slabs, in the form of cracks parallel to the slab joints, caused by aggregate which is susceptible to freezing-thawing damage (Marks and Dubberke 1982). The Iowa Department of Transportation was also dissatisfied with the length of time required to complete the freezing-thawing tests (up to 5 months) and set out to find more accurate and efficient testing procedures (IDOT 1980).

The Iowa Department of Transportation assumed that the performance of the aggregate was related to the size and amount of pores in the rock and conducted tests that injected water into pores at various pressures. The resulting Iowa Pore

Index test uses air pressure applied at 240 kPa (35 psi) to a sample covered by water (see Section 5.7. for procedure details).

The amount of water injected in the first minute is called the primary load. It is the amount of water that fills the larger pores within the rock (IDOT 1980). The primary load was found not to relate to freezing-thawing damage. This conclusion relates well to literature describing frost propagation in porous materials. The larger pores are relatively undamaged by freezing and thawing since moisture is able to migrate quickly. When water freezes and crystallises to surfaces within the pores, it does so with a concave meniscus, which allows vapour pressures to remain low and the rock is able to contract (Litvan 1981).

The amount of water injected in the next 14 minutes after the first minute and up to the end of the fifteenth minute is called the secondary load. The Iowa Pore Index Number is extrapolated from the secondary load, by finding the equivalent amount of water (in millilitres) for a standardised sample mass of 9000 grams (IDOT 1980). When the Iowa pore index number is greater than 27, concrete using that aggregate was found to be susceptible to D-cracking (IDOT 1980, Marks and Dubberke 1982). Aggregate with Iowa Pore Index Numbers greater than 27 have been shown to have a predominance of pores ranging in size from 0.04 to 0.2 µm diameter (Marks and Dubberke 1982). The authors propose that within these intermediate sized pores, moisture migrates into the pores over time but cannot migrate out at a rate fast enough when water within the pores begins to freeze into a “non-crystalline amorphous solid” (Litvan 1981). As more ice develops, the pressure increases within the pores. Failure or cracking of the rock fabric occurs when the tensile strength of the rock is exceeded. Higher moisture levels within the rock’s pores leads to greater pressures (Litvan 1981, Hermanson 1987, Stark 1989).

Aggregate with secondary loads of 27 or lower were shown to be durable with respect to D-cracking (IDOT 1980, Marks and Dubberke 1982). In this case, the porosity and degree of saturation of pores potentially affected in the second portion of the test is low and the resulting low water content is associated with less damage (Litvan 1981).

The Iowa Pore Index in aggregates was found to correlate well with D-cracking pavement inventories and also identified those rocks with a high proportion of pore sizes in the range of 0.04 to 0.2 μm diameter (Marks and Dubberke 1982). These results relate well with the theory of ice propagation through porous materials. Litvan (1981) states that solids with either very high or very low porosity perform well in freezing and thawing. The Iowa Department of Transportation has replaced its conventional freezing-thawing testing requirements with the Iowa Pore Index Test, as they are satisfied that it accurately predicts the ability of concrete aggregates to resist freezing-thawing damage. The Iowa Pore Index Test is significantly faster and more efficient than conventional freezing-thawing tests (Iowa 1980).

The text for this thesis is accompanied by a CD-ROM containing the following list of files:

2001 Riprap Measurement Data\ 2001 D1N 05-11.XLS 2001 D1N 13-19.XLS 2001 D1S 04-11.XLS 2001 D1S 14-22.XLS 2001 D1S 30-42.XLS 2001 D2N 42-47.XLS 2001 D2N 49-54.XLS 2001 D2N 55-59.XLS 2001 D2N 77-82.XLS 2001 D2S 47-55.XLS 2001 D2S 57-65.XLS 2001 D2S 67-75.XLS 2001 D2S 77-87.XLS 2001 D3S 136-143.XLS 2001 D4S 144-195.XLS	Software: Microsoft Excel 97
2002 Riprap Measurement Data\ 2002 D1N 10.XLS 2002 D1S 11.XLS 2002 D1S 36.XLS 2002 D2N 78.XLS 2002 D2S 55.XLS 2002 D2S 77.XLS 2002 D3S 142.XLS	Software: Microsoft Excel 97
Photographs\ Explanation for Photographs.DOC	Software: Microsoft Word 97
Photographs\2001\Field Study Grids\North Dykes\ 1N 05+00.jpg 1N 06+00.jpg 1N 07+00.jpg 1N 09+00.jpg 1N 10+00.jpg 1N 11+00.jpg 1N 13+00 G1.jpg 1N 13+00 G2.jpg 1N 14+00.jpg 1N 15+00.jpg 1N 17+00.jpg 1N 18+00.jpg 1N 19+00.jpg	Software: Any software that can open/view jpg format files

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