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# Bearing Capacity of Footings on Compacted Sand

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# BEARING CAPACITY OF FOOTINGS
# ON COMPACTED SAND

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## ABSTRACT

This paper presents the results of footing load tests conducted on compacted sand beds to evaluate the bearing capacity and load-displacement characteristics of shallow foundations. Tests were conducted on square concrete footings with widths of 0.30, 0.61, 0.91, and 1.22 m and with embedment ratios (D/B) of 0, 0.5, and 1.0 to investigate the influence of footing size and embedment on the load-displacement behavior and ultimate bearing capacity. A description of the soil and test procedures used is given and the results of the footing load tests are presented. A discussion of the definition of ultimate bearing capacity and the use of normalized curves to describe the footing behavior is presented. A simple model is presented that may prove useful for the design of shallow foundations on sands.

## KEYWORDS

Footings, Sand, Shallow Foundations, Bearing Capacity, Settlement

## INTRODUCTION

Shallow foundations are considered a viable economic alternative to deep foundations for highway structures constructed at dry crossings or on compacted fill. In order to make reliable estimates of foundation settlement for in service structures it has become increasingly obvious that the deformation characteristics of footings on granular soils must be related to the load intensity, relative to the ultimate or failure load conditions. This requires an accurate evaluation of the ultimate bearing capacity. During the past five years, over fifty prototype-scale footing load tests have been conducted on compacted sand beds in a test pit at the Turner-Fairbank Highway Research Center of the Federal Highway Administration. This paper presents the results of a number of these tests and compares the load-settlement performance of the footings.

## PROTOTYPE-SCALE FOOTING TESTS

Prototype-scale footing load tests were conducted at the Federal Highway Administration Turner-Fairbank Highway Research Center at McLean, Virginia. Tests were performed in a 3.5 m x 7.1 m x 6.5 m deep concrete test pit on compacted sand beds prepared at different relative densities. Sand was placed in the test pit in 0.3 m loose lifts and then compacted using a vibratory plate compactor to achieve a desired relative density. In-place density tests were performed using a nuclear moisture-density gauge at several locations around the pit on each lift to verify the density achieved with each pit fill. The sand used for the testing was a uniform fine mortar sand having a mean grain size of 0.75 mm and a uniformity coefficient of 2.6. There is a small amount of fines present in this material, generally less than 5%. Minimum unit weight of the sand is 1.41 $Mg/m^3$ and maximum unit weight is 1.70 $Mg/m^3$. Tests were conducted on sand beds of relative densities ranging from -20.5% to 75.0%. Load tests described in this paper were performed on the as compacted sand in a moist condition (i.e., with no water table present). Negative relative density was possible by using moist sand and essentially zero compactive effort. This produced in place density less than that obtained using the ASTM laboratory procedure on oven dry material as a result of bulking.

Footings were constructed of reinforced concrete and had widths ranging from 0.30 m to 1.22 m. Footings were placed at different depths in the sand to provide varying embedment ratios (D/B) ranging from 0 to 1. Incremental load tests were performed on each footing using a hydraulic ram loading system with the central vertical load measured using an electronic load cell and the vertical displacement measured at the four corners of the footing using LVDT's. Data from each of the load tests were recorded automatically on a data acquisition system as the test progressed. Each of the footing tests was conducted so that a total settlement of approximately 10% of the footing width was achieved in the test. All of the footings described herein were square. A summary of the footing tests performed at the FHWA facility and used for this paper is presented in Table 1. Results of all footing tests are

described in detail in an FHWA Research Report by Adams and Lutenegger (1998).

Table 1. Results of FHWA Prototype Footing Load Tests.

| Test Series | $D_r$ (%) | Width (m) | Depth (m) | D/B |
|---|---|---|---|---|
| 95SD4 | 45.0 | 0.30 | 0.0 | 0 |
| | | 0.30 | 0.15 | 0.5 |
| | | 0.61 | 0.0 | 0 |
| | | 0.61 | 0.61 | 1 |
| | | 1.22 | 0.0 | 0 |
| 95SD5 | 35.8 | 0.30 | 0.30 | 1 |
| | | 0.30 | 0.60 | 2 |
| | | 0.61 | 0 | 0 |
| | | 0.61 | 0.30 | 0.5 |
| | | 0.61 | 0.61 | 1.0 |
| | | 1.22 | 0.30 | 0.25 |
| 97SD1 | 50.1 | 0.30 | 0.15 | 0.5 |
| | | 0.61 | 0 | 0 |
| | | 0.61 | 0.15 | 0.25 |
| | | 0.61 | 0.30 | 0.50 |
| | | 0.61 | 0.61 | 1 |
| | | 0.91 | 0.46 | 0.5 |

## DETERMINING BEARING CAPACITY

In order to investigate the relationship between settlement and footing stress, it was important to determine the ultimate bearing capacity from each of the footing load tests in a consistent manner. In the absence of a well-defined plunging failure which can be used to identify the ultimate capacity, there are a number of methods that may be used to interpret either the "allowable" bearing capacity or the "ultimate" bearing capacity of foundations from footing load tests.

### Allowable Bearing Capacity

In most geotechnical practice, the allowable bearing capacity is obtained by first determining the ultimate bearing capacity and then reducing this value by applying an appropriate factor of safety. This approach does not consider deformation of the footing and settlement is then estimated by a separate (decoupled) calculation. If the settlement estimate is unacceptably high, the "allowable" value is further reduced until the settlement estimate is within tolerable limits set by the project. An alternative to this approach is to choose the footing stress corresponding to a limiting absolute settlement value, e.g., 25.4 mm, to give the "allowable" bearing capacity. However, this approach is arbitrary and the limiting settlement criteria could just as easily be chosen as some other value, for example, 12.7 mm. The inadequacy of this approach is that the use of a fixed value of settlement is independent of the footing size. Clearly, a settlement of 25.4 mm represents a larger *relative* displacement for a footing of width 1.0 m in comparison

to a footing of width 3.0 m (i.e., s/B = 2.5% vs. s/B = 0.8%, respectively).

### Ultimate Bearing Capacity

When results from an actual load test are available, either from some smaller plate load or prototype-scale tests or from a full scale proof load test, the ultimate bearing capacity may be estimated directly from the footing performance. However, because the load-settlement curve may be subject to interpretation it is necessary to be consistent in defining the ultimate bearing capacity value from the test data, especially when there may be several tests available. The most common methods for evaluating the ultimate bearing capacity from a footing load test include:

1) choosing the footing stress corresponding to a limiting *relative* settlement value (e.g., s/B = 10%) ( Briaud and Jeanjean 1994); this model is referred to as the 0.1B Method;

2) choosing the footing stress corresponding to a distinctive marked change in the settlement, (e.g., the intersection of the initial and final tangent slope of the stress vs. settlement curve) (Trautmann and Kulhawy 1988); this model is referred to as the Tangent Intersection Method;

3) manipulating the footing stress vs. settlement data and then selecting the footing stress corresponding to an intersection point (e.g., log stress vs. log settlement) (DeBeer 1970); this method is referred to as the Log-Log Method;

4) choosing a reasonable model to fit the stress vs. settlement data and extrapolating to the asymptotic value corresponding to an upper limit of stress; referred to as the Hyperbolic Method.

Each of these interpretation methods may give a different value of bearing capacity and therefore it may be important to select a single method in order to be consistent. These methods are illustrated in Figure 1 for a typical footing test. The first three methods are selfexplanitory. The Hyperbolic Method makes use of a simple hyperbolic model expressed as:

$$s/Q = a + bs \qquad (1)$$

where: s = settlement, Q = foundation stress, and a and b are regression constants. The ultimate bearing capacity is obtained from the inverse slope of this linear relationship as 1/b. This model has been used in the past to describe the load-displacement behavior of plate loading tests and footings (e.g., Chin 1983, Wrench and Nowatzki 1986, Ghionna et al. 1991, Wiseman and Zeitlan 1994, Thomas 1994).

Table 2 presents a comparison of the interpreted ultimate bearing capacity using each of these four methods for the footing tests summarized in Table 1. In general it can be seen that the interpreted ultimate bearing capacity increases according to: Log-Log Method < Tangent Intersection Method < 0.1B Method < Hyperbolic Method. The 0.1B Method and the Hyperbolic Method are the only methods that make use of the full load-settlement curve to estimate ultimate capacity and produce much larger settlements at failure than the other two methods.
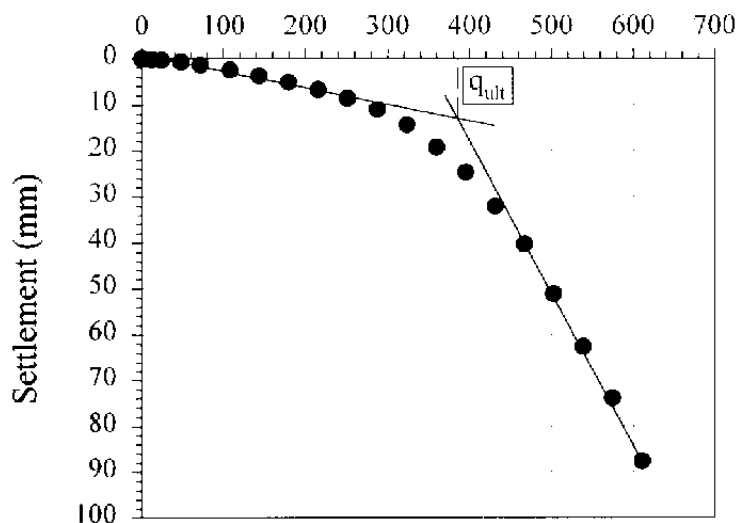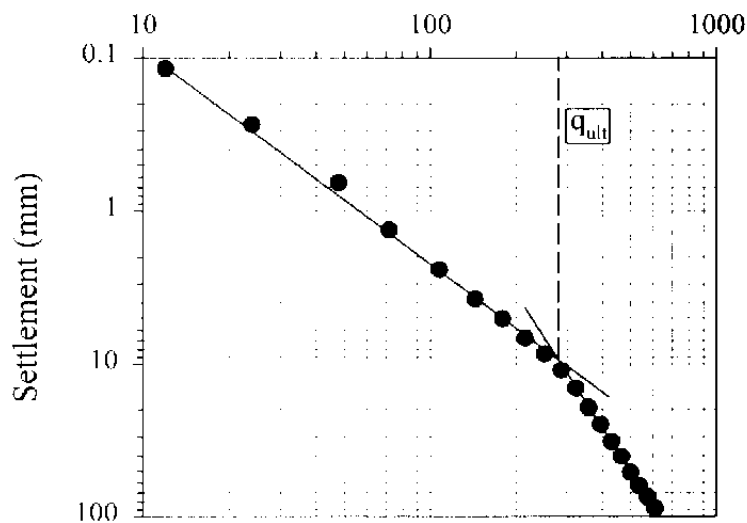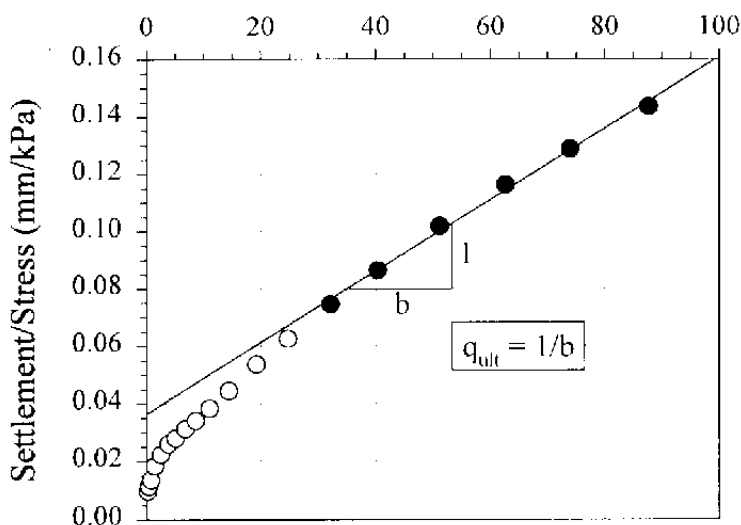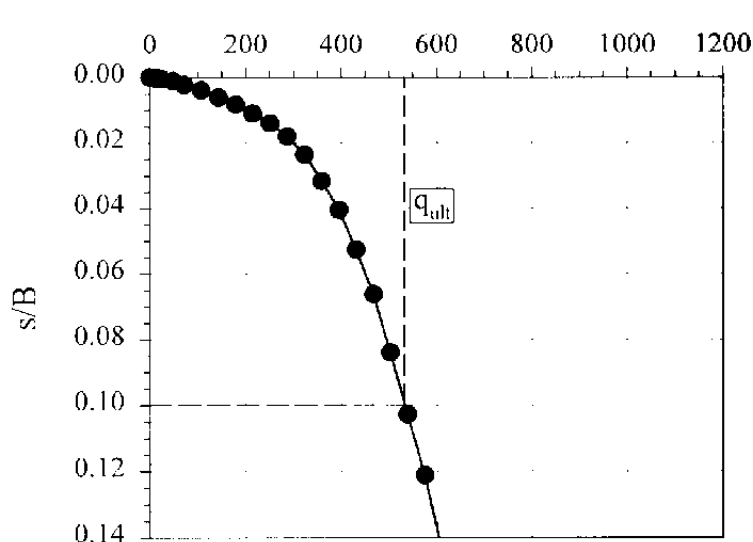
Figure 1. Different Methods for Defining Ultimate Bearing Capacity of Shallow Foundations from Load Test Results.

## FOOTING BEHAVIOR

To illustrate the importance of coupling the settlement of footings to the applied footing stress, results obtained from a number of footing tests are presented in the following sections.

### Constant Width - Varying D/B

The influence of increasing depth (D/B) on the behavior of a footing of constant width is illustrated in Figure 2. The stress-settlement curves obtained from three footing tests shown in Figure 2a clearly illustrate that the behavior changes with relative depth as predicted by conventional bearing capacity theory. Even when the results are presented in the form of stress vs. relative settlement (s/B) as shown in Figure 2b, the influence of footing depth is clear. The relative settlement is the settlement divided by the foundation width, B, and can be considered to represent in some way an estimate of the strain level in the soil under the foundation,

Table 2. Interpreted Ultimate Bearing Capacity Using Different Methods.

| Test Series | Width (m) | Depth | $q_{ult}$ (kPa) | | | |
|---|---|---|---|---|---|---|
| | | | TI | LL | HYP | 0.1 B |
| 95SD4 | 0.30 | 0 | 265 | 270 | 295 | 280 |
| | 0.30 | 0.5B | 370 | 310 | 618 | 400 |
| | 0.61 | 0 | 262 | 220 | 483 | 355 |
| | 0.61 | 1B | 450 | 405 | 1232 | 785 |
| | 1.22 | 0 | 330 | 210 | 717 | 580* |
| 95SD5 | 0.30 | 1B | 415 | 310 | 783 | 435 |
| | 0.30 | 2B | 628 | 440 | 1470 | 790 |
| | 0.61 | 0 | 328 | 300 | 502 | 411 |
| | 0.61 | 0.5B | 387 | 310 | 805 | 536 |
| | 0.61 | 1B | 655 | 620 | 1451 | 915 |
| | 1.22 | 0.25B | 527 | 410 | 1098 | 900* |
| 97SD1 | 0.30 | 0.5B | 720 | 680 | 840 | 755 |
| | 0.61 | 0 | 495 | 500 | 547 | 508 |
| | 0.61 | 0.25B | 740 | 500 | 939 | 800 |
| | 0.61 | 0.5B | 710 | 760 | 1361 | 1110 |
| | 0.61 | 1B | 910 | 790 | 1774 | 1320 |
| | 0.91 | 0.5B | 890 | 720 | 1752 | 1350 |

* Extrapolated

assuming that the zone of influence is related to the width B. However, the authors have found from detailed instrumentation on a number of the footing tests that the zone of influence may be related to other variables such as relative load intensity, depth of embedment, relative density, etc. The use of footing stress vs. s/B curves produces more-or-less single response only at very low values of s/B; typically less than about 1% and therefore is not sufficient for describing the full response of the footings under all loads.

When the results are normalized further and presented as normalized footing stress or relative load intensity ($q/q_{ult}$) vs. relative settlement, it can be seen that a single curve is obtained for all values of D/B as shown in Figure 2c. The surface footing actually shows erratic results which may be the result of the plunging failure observed. In this case, the ultimate bearing capacity has been defined using the 0.1B Method previously described. These results suggest that a single unifying concept may be used to describe the behavior of all three footings for the varying test conditions used. Since different methods may be used to define the ultimate bearing capacity from the load test results, it is of interest to evaluate the influence of the method on the normalized footing behavior. Figure 3 presents normalized load curves for the same test results as presented in Figure 2 using the other methods for defining ultimate bearing capacity. It can be seen that with the exception of the Hyperbolic Method, a single curve is obtained which describes the footing behavior. This is especially true for the portion of the curve of most interest to engineers, i.e., that part

below a value of $q/q_{ult} = 0.33$, corresponding to a Factor of Safety = 3.0. Note that in this range of the curve, the relative settlement is small, but different, depending on which method is used to define the ultimate bearing capacity.

Results of a different pit fill series with the sand at a lower relative density are shown in Figure 4. Again it can be seen that the when the test results are expressed as relative stress vs. relative settlement the individual load curves fall onto a more-or-less single curve describing the behavior of all of the footings.

Constant D/B - Varying Width

Footing tests performed in which the footing width B was varied and the relative embedment was held constant were also evaluated to determine if the results could be described using normalized behavior. Test results for three surface footing tests (D/B = 0) are shown in Figure 5. It can be seen that in this case, there appears to be very little difference in the individual load test results, except at high values of relative stress. As with the results previously shown in Figure 2, the plunging behavior leads to less predictable behavior. An additional set of tests for a constant footing width in which D/B = 0.5 is shown in Figure 6. These results are almost identical to the previous set of tests performed at D/B = 0. In both cases the 0.30m footing showed a plunging failure.
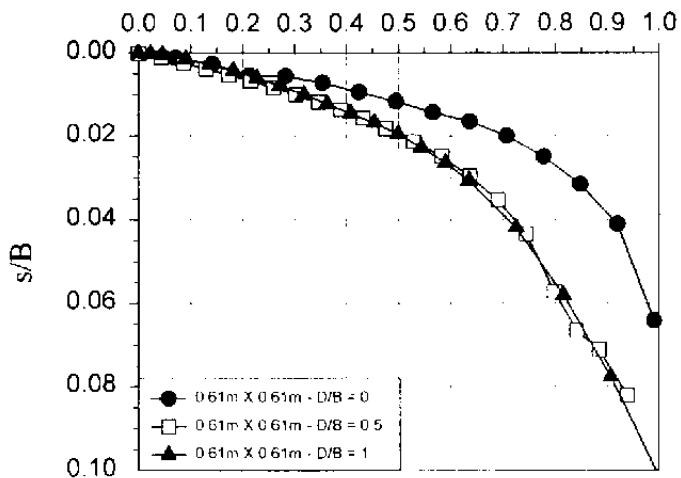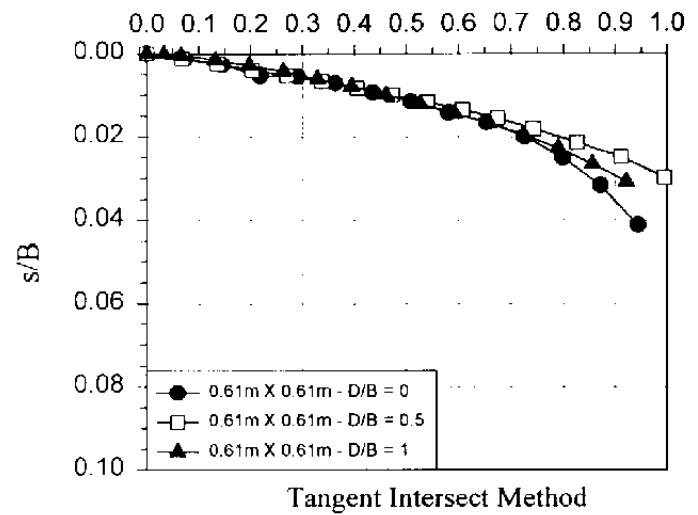
## 97SD1

### Stress (kPa)
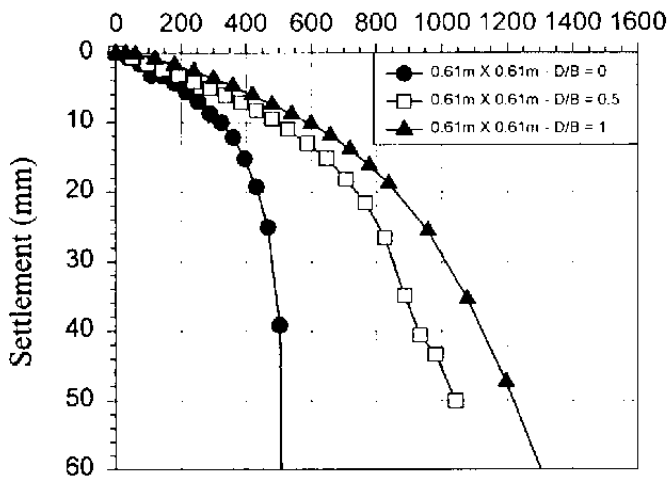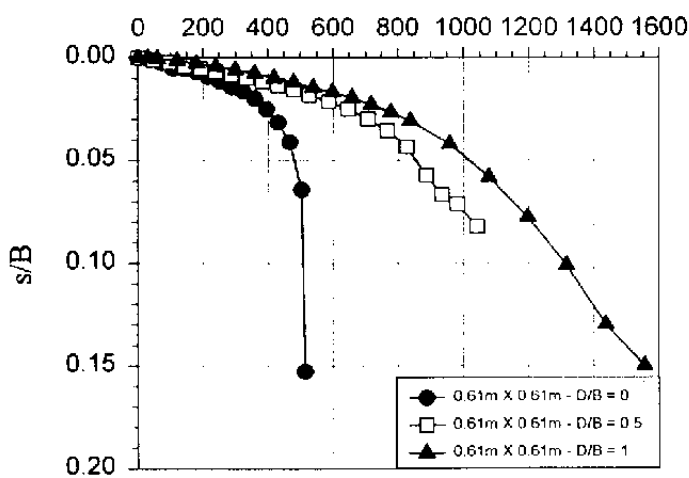


## 97SD1

$q/q_{ult}$



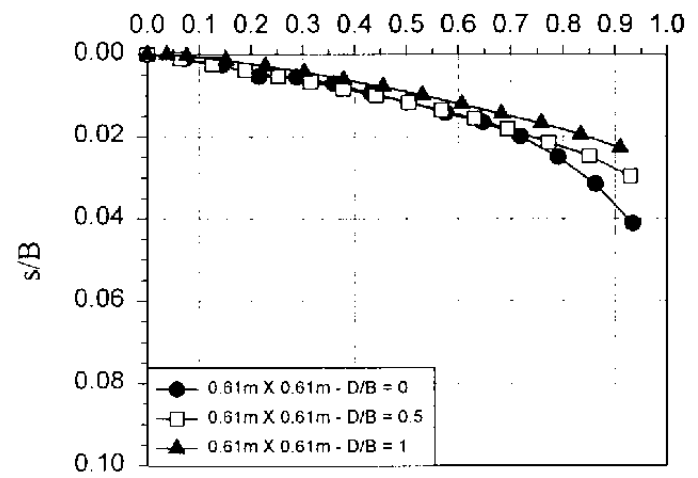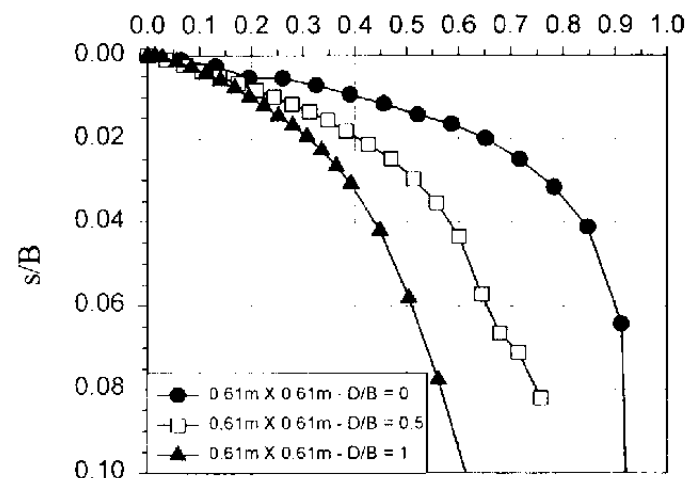Tangent Intersect Method

### Stress (kPa)



$q/q_{ult}$



Log - Log Method

$q/q_{ult}$
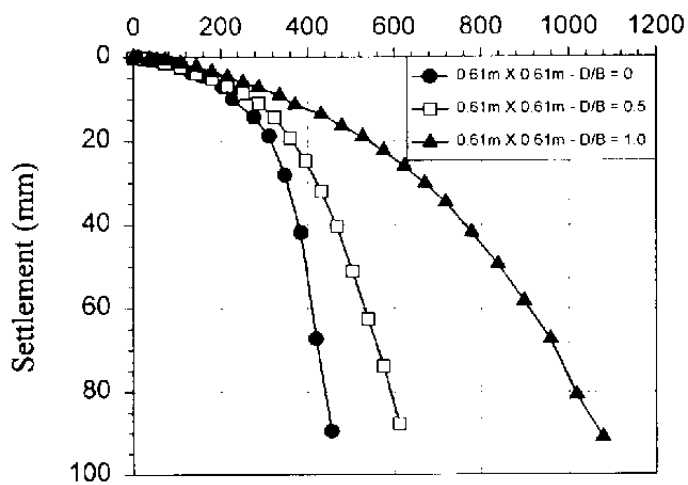


0.1B Method

$q/q_{ult}$



Hyperbolic Method
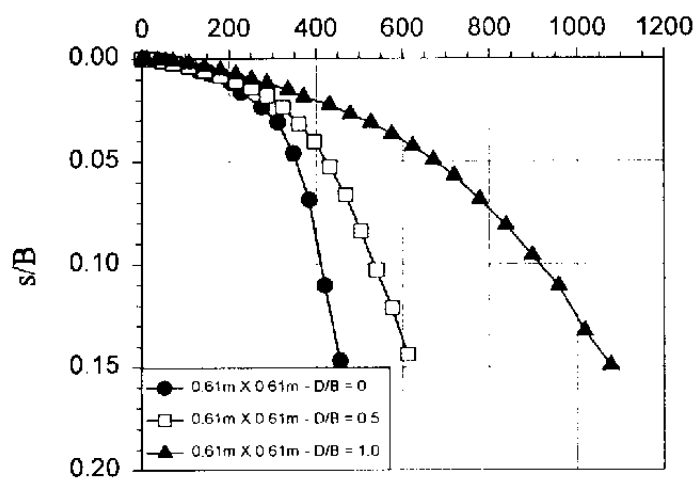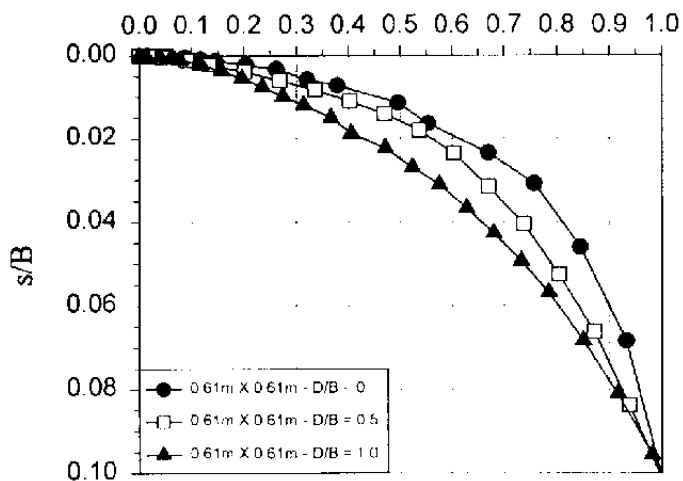
*Figure 2. Results of Footing Load Tests for Varying D/B.*

*Figure 3. Normalized Curves Using Different Methods to Define Ultimate Bearing Capacity.*
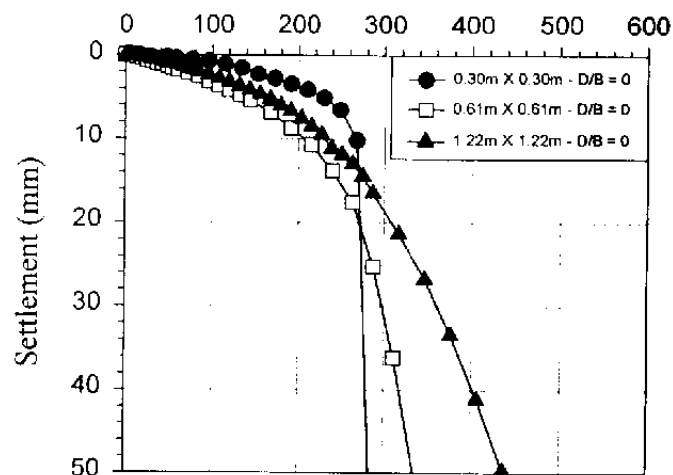
## 95SD5

**Stress (kPa)**

Legend:
- 0.61m X 0.61m - D/B = 0
- 0.61m X 0.61m - D/B = 0.5
- 0.61m X 0.61m - D/B = 1.0

Settlement (mm)

**Stress (kPa)**

s/B

- 0.61m X 0.61m - D/B = 0
- 0.61m X 0.61m - D/B = 0.5
- 0.61m X 0.61m - D/B = 1.0

**q/q_{ult}**

s/B

- 0.61m X 0.61m - D/B = 0
- 0.61m X 0.61m - D/B = 0.5
- 0.61m X 0.61m - D/B = 1.0

0.1B Method

## 95SD4

**Stress (kPa)**

Legend:
- 0.30m X 0.30m - D/B = 0
- 0.61m X 0.61m - D/B = 0
- 1.22m X 1.22m - D/B = 0

Settlement (mm)

**Stress (kPa)**

s/B

- 0.30m X 0.30m - D/B = 0
- 0.61m X 0.61m - D/B = 0
- 1.22m X 1.22m - D/B = 0

**q/q_{ult}**

s/B

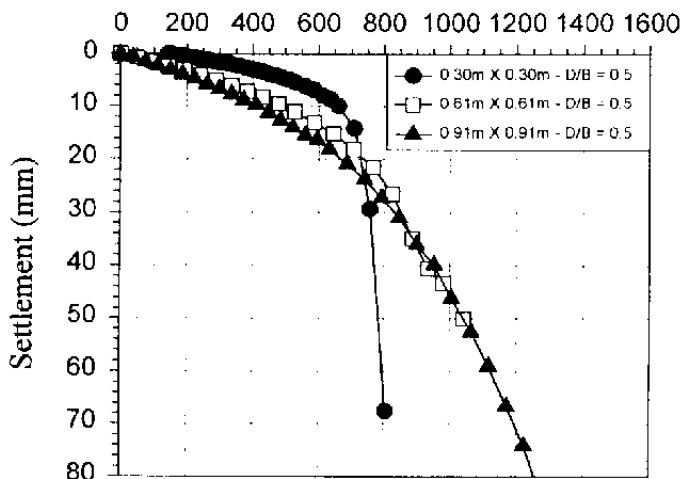- 0.30m X 0.30m - D/B = 0
- 0.61m X 0.61m - D/B = 0
- 1.22m X 1.22m - D/B = 0
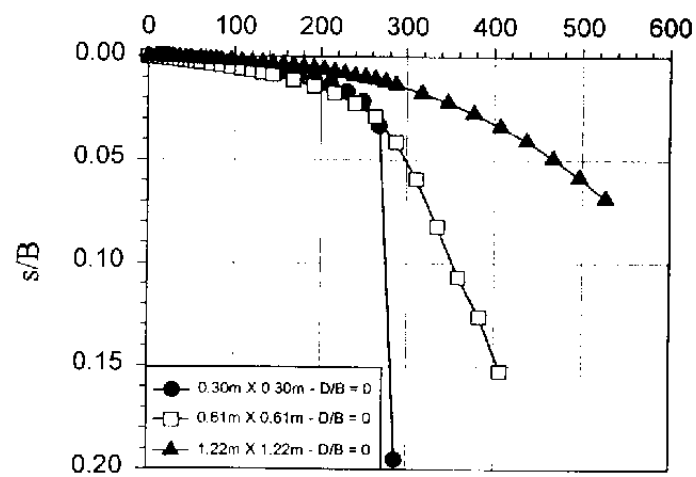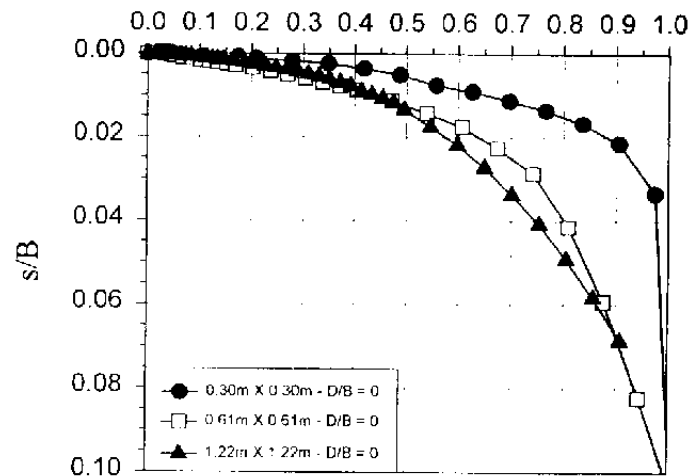
O.1B Method

*Figure 4. Results of Footing Load Tests with Varying D/B.*

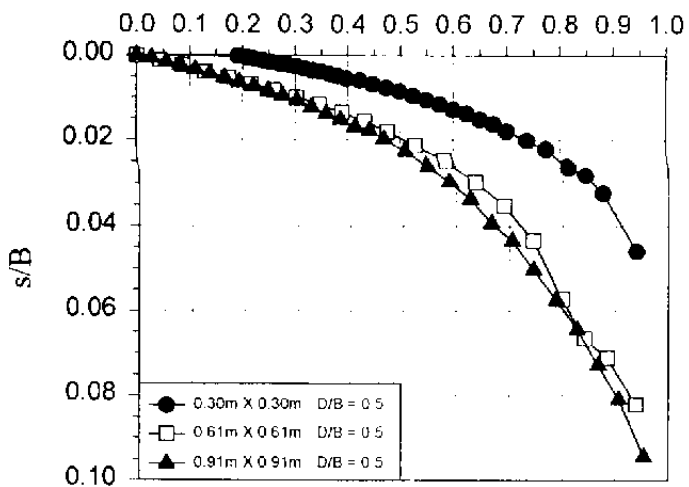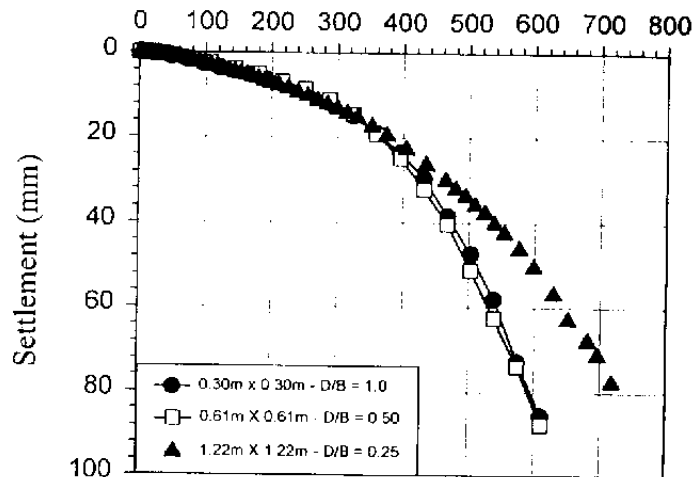*Figure 5. Results of Footing Load Tests with D/B = 0.*

97SD1
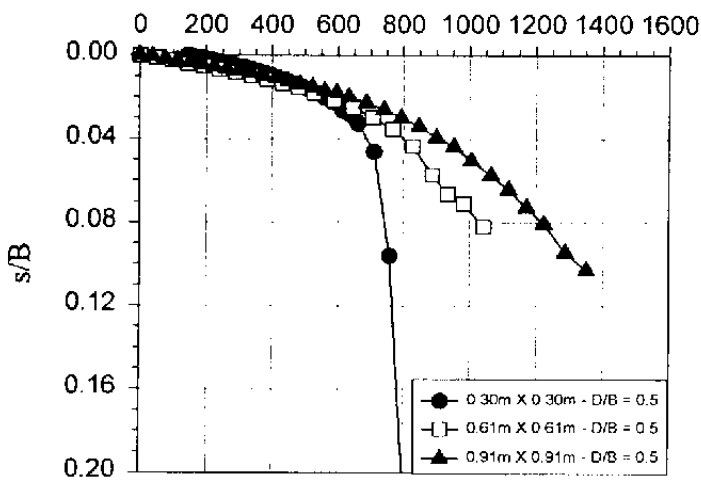
95SD5
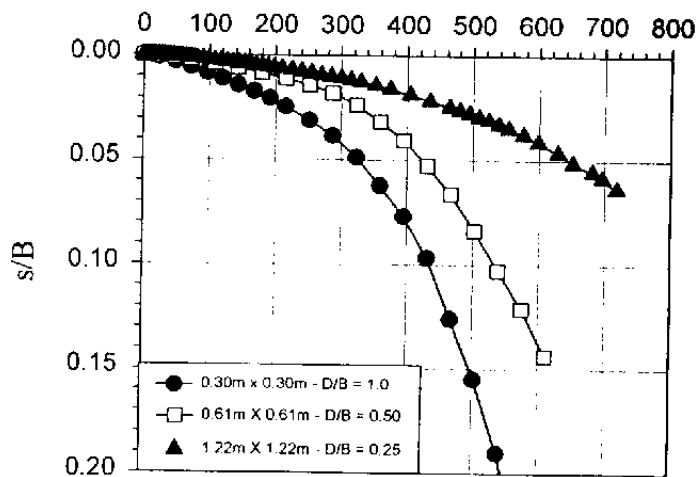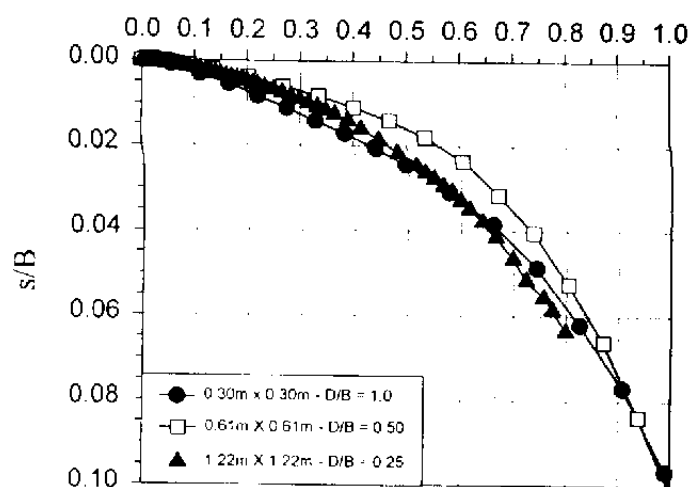


Figure 6. Results of Footing Load Tests with D/B = 0.5.

Figure 7. Results of Footing Load Tests with Constant Depth.

As a final consideration, tests were conducted using footings of varying width placed at the same <u>depth</u> . The result is that each of the footings has a different relative embedment (D/B). These results are shown in Figure 7. In this case, it can be seen that even though the individual curves of footing stress vs. settlement generally fall onto a single curve, when the relative settlement is plotted against the footing stress the curves show distinctly different behavior. The use of the normalized concept results in a single curve as before.

## MODEL FOR EVALUATING FOOTING BEHAVIOR

The previous test results have shown that the behavior of shallow foundations on sands can be placed in a framework using a singular concept of normalized behavior. Steenfelt (1989) has suggested that the behavior of spread footings may be approximately described from the simple expression:

$$(s/s_f) = (P/P_f)^x \qquad (2)$$

where:
s = settlement at any load P
$s_f$ = settlement at the failure load $P_f$
x = an exponent typically in the range of 2 to 3.

It appears that this model may have merit in describing the behavior of the footing tests conducted in this study and the model was applied to the test data. An example of this approach is illustrated in Figure 8 using the footing load test results previously shown in Figure 2. Using the 0.1B Method to define the ultimate bearing capacity, the value of $s_f$ is automatically known and $q_{ult}$ was then taken from the individual load curves. As shown in Figure 8, these results show a very consistent trend of the exponent x decreasing with D/B. In the absence of sufficient test data to produce a relative settlement of 10%, the Hyperbolic Method may be used to define the ultimate bearing capacity. The authors have found that on average, the 0.1B Method ultimate bearing capacity is 75% of the Hyperbolic Method value.

In design practice therefore, this model could be applied by first estimating $q_{ult}$ using an appropriate bearing capacity theory. Using $s_f$ as 0.1B, the value of s for any q may then be estimated. This approach then couples the estimate of footing settlement to the level of working stress through the relative load intensity.

## CONCLUSIONS

Results of a number of footing test performed on compacted sand have been presented. The test results have been used to demonstrate that the test data may be presented in a normalized technique to describe the deformation behavior of a footing for a variety of conditions. The single most significant result illustrated by the test results presented is that the settlement and bearing capacity of shallow foundations on sand are uniquely related. The performance of footings must be considered the result of the coupling of deformation as a function of the relative load intensity.
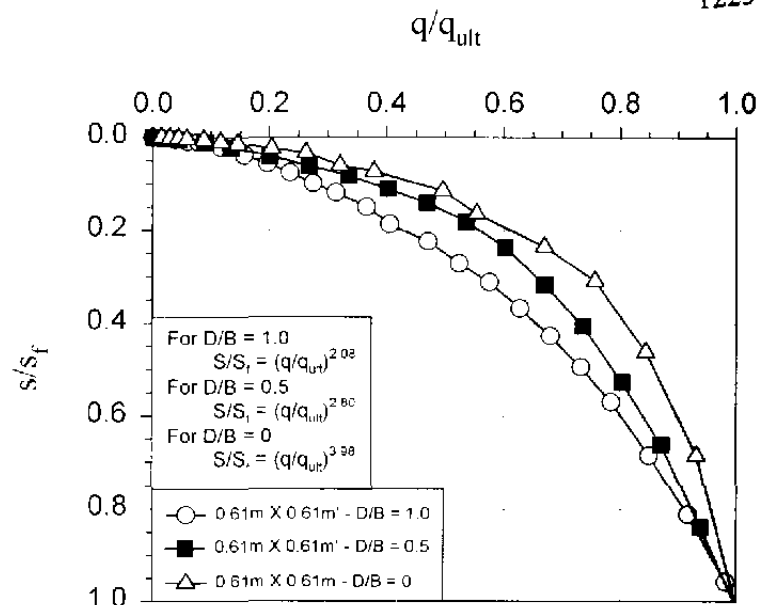


*Figure 8. Normalized Footing Behavior.*

The test results suggest that a simple model may be appropriate for describing the behavior of shallow foundations on sands and therefore may be very useful for design. The results of the footing load tests presented in this paper and the results of all tests performed are being evaluated further to determine which method of defining ultimate bearing capacity compares best with classical bearing capacity theory. Additionally, it is necessary to determine what other variables (both soil and foundation) may affect the normalized behavior described and how this may affect the simple model suggested by Equation 2 and Figure 8. Finally, the method of defining ultimate bearing capacity may influence the model described by Equation 2 and must be investigated.

## ACKNOWLEDGMENTS

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