Shear Strength of Estuarine Muds of the Swan River

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SUMMARY This paper summarises data collected over many years on the shear strength properties of the estuarine muds encountered at highway bridge sites on the Swan River, Perth, Western Australia. Various methods have been used to determine shear strength. The results obtained are related to values derived from the computer analysis of slip failures which occurred in trial embankments or during construction. It was concluded by the authors that Bjerrum's (1972) shear strength correction factors in combination with a factor of safety against slip of 1.2 should result in economical and safe designs in most cases.

1 INTRODUCTION
Since 1960 the development of the road network in Perth has necessitated bridging the Swan River at several locations. The sites of these bridges have been generally characterised by the existence of estuarine muds. These muds have proved foundation problems for bridge designers. The location of sites referred to in this paper are shown in Figure 1. The estuarine deposits are of recent geological origin and have resulted from the deposition of fine grained material in the slow moving meander section of the Swan River where it crosses the coastal plain.

![Figure 1 Location of MRD bridge sites on the Swan River](image)

Investigations of bridge sites over time have enabled the Main Roads Department, Western Australia to assemble valuable data derived from various methods of determining in situ shear strength and to relate this data to values obtained by computer analysis of actual slip failures, both induced and unintentional.

2 NOTATION
- $C$ = cohesion (kPa)
- $C_u$ = undrained cohesion (kPa)
- $D$ = vane diameter (m)
- $F$, $F_p$, $F_c$ = factor of safety
- $H$ = mud depth (m)

- $k_1$ = constant determined from vane dimensions
- $k_2$ = constant relating vane shear strength to point resistance
- $m$ = sum of moments mobilising failure (kNm)
- $m_p$ = sum of moments resisting failure (kNm)
- $P$ = pressure (kPa)
- $P_t$ = limit pressure (kPa)
- $P_I$ = plasticity index
- $q_c$ = point resistance (kPa)
- $S$ = shear strength (kPa)
- $S_u$ = undrained shear strength (kPa)
- $S_v$ = shear strength as determined by shear vane tests (kPa)
- $T$ = torque (kNm)
- $N_V/V_d$ = volumetric strain
- $\gamma_b$ = buoyant unit weight (t m$^{-3}$)
- $\gamma_s$ = saturated unit weight (t m$^{-3}$)
- $\phi$ = angle of internal friction ($^\circ$)
- $\alpha$ = effective normal pressure (kPa)
- $u$ = correction factor relating vane shear strength to actual calculated shear strength
- $\tau$ = required shear strength (kPa)

3 THE OCCURRENCE OF ESTUARINE MUDS
In geological terms, the coastal plain section of the Swan River is very recent and its form has been greatly influenced by eustatic changes during the last 14,000 years. Research in sea level changes reported by Churchill (1959) has shown that the sea level has risen 70 metres during this period. With the rise in sea level, there has been a corresponding reduction of the velocity of flow in the river and the meander pattern has become more pronounced. This in turn has led to the deposition of fine grained sediments in stretches of slack water and in overbank spill. Hence, estuarine muds have been encountered at Mounts Bay (now reclaimed), Durswood Peninsula, Grandstand Road Bridge and Bayswater.

4 SLOPE STABILITY
The large scale movement of a soil mass both downward and outward is commonly referred to as a slip failure. The theoretical stability, (or instability), of a slope may be expressed in terms of a factor of safety ($F$), where a value of $F = 1$ indicates a critical stability state.
F may be defined in terms of the ratio of available shear strength (S) to required shear strength (T)

\[ F_S = \frac{S}{T} \]  \hspace{1cm} (1)

Other definitions such as

\[ F_C = \frac{C_C}{C_a} \]  \hspace{1cm} (2)

where \( C_C \) is the cohesion required for stability with full friction mobilised; and \( C_a \) is the actual cohesion;

or

\[ F = \frac{m_p}{m} \]  \hspace{1cm} (3)

where \( m_p \) is the sum of the moments resisting failure; and \( m \) is the sum of moments mobilising failure have been used.

The reader is referred to Winterkorn and Fang (1975) for a summary of some of the more common methods for determining \( F \).

However, prediction and performance rarely correspond exactly in slope stability analysis for a number of reasons, including the following

- Non-homogeneity of the soil.
- Actual failure surfaces differ from the idealised straight lines, circular arcs or logarithmic spirals used in most analytical methods.
- Actual failures are a three dimensional phenomenon whereas most methods of analysis are based on two dimensional considerations.
- Real soil behaviour is more complex than that implied by the limit state equilibrium approach used in most slope stability analysis methods.
- Actual soil properties (e.g. shear strength) may differ from those predicted from in situ and laboratory tests.

5 SHEAR STRENGTH

The ability for a slope to remain stable is in many cases related to the properties of the soil existing beneath it. Most importantly, the shear strength of the underlying soil must be able to resist the imposed shear stresses. Due to its importance, there exist many methods, both in the field and the laboratory, for determining the shear strength.

The most common form of laboratory test involves the undrained triaxial test, where shear strength (S) is obtained from cohesion (C), normal effective stress (\( \sigma \)) and angle of internal friction (\( \phi \)) according to the equation

\[ S = C + \sigma \tan \phi \]  \hspace{1cm} (4)

The following field tests provide the most common methods of determining in situ shear strength.

5.1 Vane Shear Test

The torque (T) required to cause a vane of known dimensions to shear in situ soil is measured. This torque is then related to the soil's undrained strength, peak or remoulded depending on technique, by an equation of the form

\[ S_V = \frac{2T}{\pi D^2 (m)} \]  \hspace{1cm} (5)

5.2 Dutch Cone Test

The resistance (q_c) which a cone encounters when it is forced into the ground at a constant rate, is measured. This resistance may then be related to the vane shear strength (S_V) by an equation of the form

\[ S_V = \frac{q_c}{k_2} \]  \hspace{1cm} (6)

5.3 Pressuremeter Test

When a cylindrical cavity is expanded within a bore hole, the following expression may be assumed

\[ P = P_L + C_u \ln \left( \frac{V}{V_0} \right) \]  \hspace{1cm} (7)

Thus, if pressure (P) is plotted against the natural logarithm of volumetric strain (\( \Delta V/V_0 \)), the slope of the linear portion of the resultant graph equals the undrained cohesion (C_u).

6 CASE STUDIES

Since early 1963 several major road bridges have been constructed, or are in the process of being constructed, along the Swan River. At all of these sites a slip failure, which in some cases was intentional, occurred. For each site, back analysis was performed in an attempt to compare the embankment conditions at failure with those predicted from theory.

A correction factor (\( \mu \)) was derived which, when multiplied by the shear strength, as measured by the vane shear apparatus, gave a factor of safety equal to one for the embankment height and slope as it existed immediately prior to failure being observed.

\[ S = \mu S_V \]  \hspace{1cm} (8)

It should be recognised that this factor is not an unique property of the soil but is dependent on the method of analysis used and the accuracy to which the variables of analysis are determined.

6.1 Slip 1

**Location:** Narrows Interchange Site  
**Date:** 1963  
**Type:** Trial Embankment Loaded to Failure  
**Method of Analysis:** Swedish Slip Circle  
**Calculated Theoretical Factor of Safety (F):** 1.1  
**Vane Shear Correction Factor (\( \mu \)):** 0.9  
**Plasticity Index:** \( \approx 100\% \)  
**Reference:** Jones and Marsh (1965)
6.3 Slip 3

Location: Grandstand Street, Belmont  
Date: July 1971  
Type: Embankment Failure During Construction  
Method of Analysis: Bishop's Simplified (STABL)  
Calculated Theoretical Factor of Safety (F): 1.19  
Vane Shear Correction Factor (\(\mu\)): 0.8  
Plasticity Index: 50%  
Reference: Tatam (1983)

Note: At the time of failure, large quantities of fill were placed rapidly. It is suggested that the failure shape used for analysis is not that at which failure commenced. The calculated factor of safety may therefore be misleading.

6.6 Slip 6

Location: Beechboro-Gosnells Highway, Bayswater  
Date: July 1983  
Type: Trial Embankment Loaded to Failure  
Method of Analysis: Bishop's Simplified (STABL)  
Calculated Theoretical Factor of Safety (F): 1.15  
Vane Shear Correction Factor (\(\mu\)): 0.9  
Plasticity Index: 47%  
Reference: Hood (1983)

The vane shear correction factors were plotted with respect to Plasticity Index and superimposed on the correction chart proposed by Bjerrum (1972) as shown in Figure 2. It is apparent that a single unique correction factor could not be identified. It is suggested by the authors that the use of Bjerrum's correction factor in conjunction with a modest factor of safety (\(= 1.2\)) would provide an economical and safe design in most cases.

Figure 2 Bjerrum's correction chart
VARIATION IN SHEAR STRENGTH BETWEEN SITES

A comparison was made between shear strengths measured at each site. A linear regression analysis was carried out between shear strength, as measured with the vane apparatus, and depth. Results from above the water table were excluded to eliminate the effect of desiccation. The results are shown at Figure 3.

![Graph of Vane Shear Strength](image)

**Figure 3** Variation of vane shear strength with depth for Swan River sites

No clear trends were evident from this study though there is a tendency for shear strength to increase when moving upstream from the river mouth.

8 STATIC CONE PENETRATION TEST RESULTS

For the Burswood Peninsula and Beechboro-Gosnells Highway sites, in situ tests were carried out using an electric friction cone penetrometer of a type similar to that shown at Figure F5.1.4 of Australian Standard 1289.

For the Burswood Peninsula site, the cone penetration test results carried out in 1983 in virgin material were compared to the vane shear tests carried out in 1971. This comparison gave a relationship

\[ S_V = \frac{q_c}{10.9} \]  

for the Beechboro-Gosnells Highway site in Bayswater, vane shear tests and cone penetration tests were carried out in close proximity. Results in one area of the site gave

\[ S_V = \frac{q_c}{10.9} \]  

and in another area

\[ S_V = \frac{q_c}{9.8} \]

These results are similar to those reported by Sangerat (1972) for tests in Great Britain where cone penetration was generally of the order of 9 to 9.5 times undrained cohesion using a cone of a type similar to that used by the Main Roads Department, Western Australia.

9 PRESSUREMETER TEST RESULTS

Determination of the undrained shear strength from the self-boring pressuremeter test was carried out for the Beechboro-Gosnells Highway site at depths of 6.5 metres and 12.5 metres only. The results are presented in Table I.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Vane Shear Strength (kPa)</th>
<th>Undrained Cohesion from Self-Boring Pressuremeter (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>25</td>
<td>34</td>
</tr>
<tr>
<td>12.5</td>
<td>31</td>
<td>54</td>
</tr>
</tbody>
</table>

While this is too small a sample on which to base any definite conclusions, the results are not encouraging, particularly when it is noted that the in situ field strength, as indicated by the slip failures, was less than the shear strength measured with the vane apparatus.

10 CONCLUSION

The results of site investigations for embankment construction at four locations along the lower reaches of the Swan River have been described. Soft to very soft estuarine muds were found at all sites.

Back analysis of slip failures at all sites resulted in a range of correction factors to apply to vane shear test results, from 0.6 to 0.9. No clear relationship with Plasticity Index was apparent. However, it is suggested by the authors that the use of Bjerrum's (1972) factors in combination with a factor of safety of 1.2, could result in economical and safe designs in most cases.

Analysis of the results of electric friction cone probes suggest that the vane shear strength can be estimated from the equation

\[ S_V = \frac{q_c}{10} \]  

The self-boring pressuremeter apparatus has not been used extensively on the soft estuarine muds of the Swan River. The results from the two tests with which the authors were associated, gave results significantly different to the vane shear tests.

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REFERENCES


