Full Scale Test Loading of a Bulkhead Structure

Essai Statique à Grandeur Réelle d'un Rideau de Palplanches

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SYNOPSIS Test loading was undertaken on an ore dock to determine the potential for increasing pile heights. The soil behind the bulkhead dock structure is fill and sand overlying 6 to 9 m of stiff varved clay of concern. Inclinometers, piezometers, extensometers and precise surveys were used to monitor the controlled placing of a 26 m high limestone test loading. This generated pore pressures of up to 0.73 times the applied pressure, lateral movements of up to 13 mm and anchor rod relaxation. Pore pressures decreased by 50 per cent within one month. Effective stress stability analyses indicated a minimum safety factor of 1.2 for the test loading, that would decrease to less than unity for a full 20.7 m high ore loading. Finite element analyses confirmed the elastic nature of observed movements, and anchor relaxation. It is concluded that staged loading can be used to increase the varved clay's strength to permit full ore loading.

INTRODUCTION

The test loading programme described herein was undertaken to determine the geotechnical and structural stability characteristics of the Algoma Sault Ste Marie ore dock area shown in Figure 1, and to study the possible increasing of ore dock storage capacity to handle seasonal shipping requirements in the Upper Great Lakes. Previous studies had indicated that the dock composite structure of a timber pile supported concrete deck carying ore bridge rails, faced with a steel sheet pile anchored bulkhead of 9.5 m free height (Figure 2), had a marginal safety factor against current loadings. Increased rates of dock loading using large self-unloading ships had resulted in accelerating lateral movements of the ore dock since 1977 as shown clearly in Figure 3, even though the overall annual tonnage was not increasing, both for the steel sheet pile extension of concern here and the adjacent crib wall section that was considered in the overall test loading programme (i.e., there was a similar detailed test loading for the crib wall section).

The soil behind the structure consists of 4 m of fill and sand overlying 6 to 9 m of stiff varved clay of concern in terms of shear strength, pore pressure generation due to repetitive loading, strain softening and lateral spreading; with very stiff varved silt and very dense sand till below. Deep seated shear failure of an adjacent area occurred in 1913, and large displacements of the structure in 1944 resulted in loading restrictions that could not be lifted on the basis of several subsequent studies.

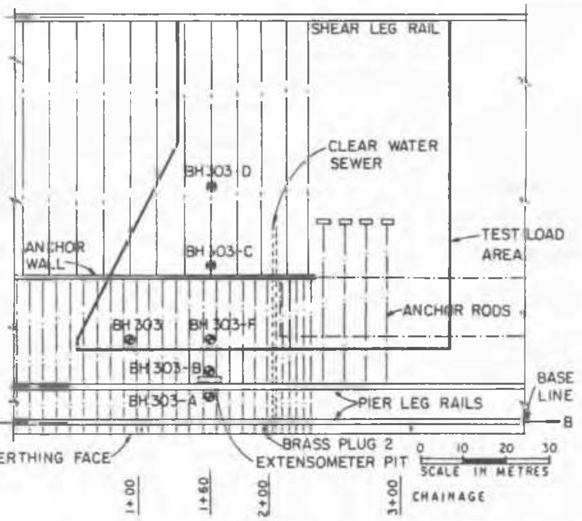


Fig.1 Test Load Area Plan and Instrumentation

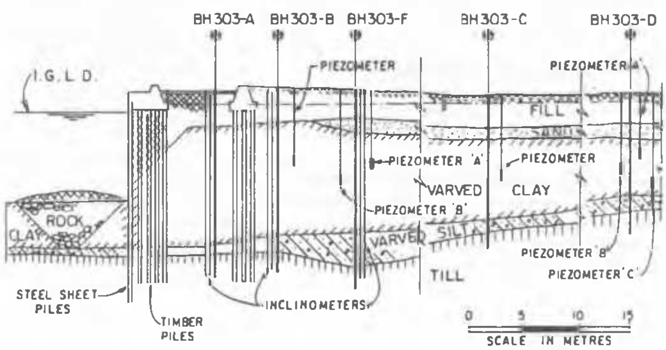
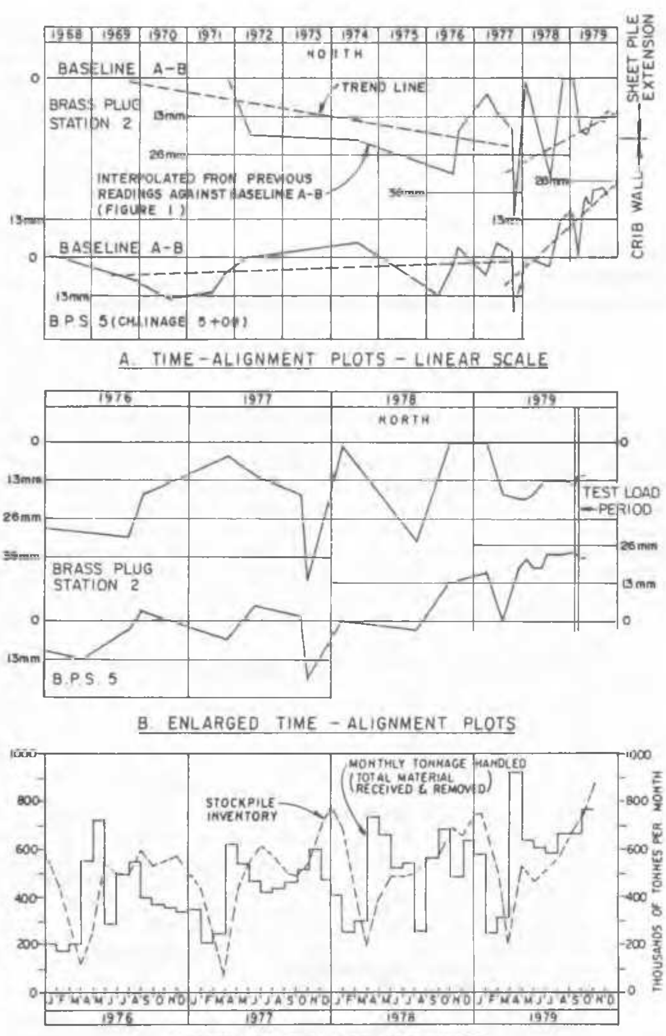


Fig. 2 Test Load Section with Soil Profile and Instrumentation



A. TIME-ALIGNMENT PLOTS - LINEAR SCALE

B. ENLARGED TIME - ALIGNMENT PLOTS

C. ORE YARD TONNAGE STATISTICS

Fig. 3 Time-Alignment Plots and Ore Yard Loading Data

Within this context of low safety factors and large deformations that are typical to many dock areas on the Great Lakes involving reclaimed land and marine clays, it was desired to deepen the berths by about 0.6 m and increase the height of ore pellet storage closer to the bulkhead. To address this, a prototype test loading programme was developed to examine the current and future stability of the ore docks, in conjunction with a detailed geotechnical investigation, monitoring, effective stress stability checks and elastic finite element method analyses. The programme will be mainly described through the report figures as a case study with some amplifying discussion in following sections.

SOIL CONDITIONS AND INSTRUMENTATION

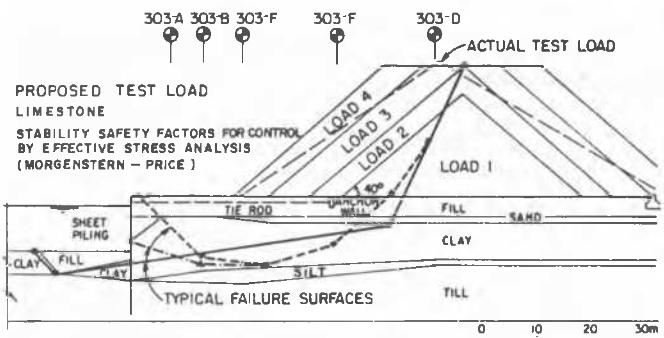
The soil conditions and properties were determined for the section of interest through a number of sampled boreholes (Figure 2), field vane and pressuremeter tests, undrained and consolidated drained triaxial tests, consolidation tests and laboratory vane tests in the horizontal and vertical direction to examine the anisotropy of the varved clay. The consolidation tests indicated the clay to have a preconsolidation pressure of 0.20 to 0.34 MPa and overconsolidation pressure of 0.12 to 0.20 MPa. On the basis of all the strength testing, the average undrained shear strength of the varved clay was 57.5 kPa with effective parameters $\phi' = 25°$ and $c' = 0$. Only slight anisotropy was found and it is considered that little strength gain had occurred due to previous loadings. Properties of the test loading limestone were 1440 kg/m³ and 38° (angle of repose); as compared to 2384 kg/m³ and 26° for ore pellet loadings.

The instrumentation consisted of inclinometers, pneumatic piezometers, extensometers, and precise horizontal and vertical surveys as indicated on Figures 1, 2 and 3. This instrumentation was designed to both control the prototype loading, and to provide data for predicting stabilities for future loadings.

TEST LOADING AND ANALYSES

The test loading was completed under the set of control conditions in Table 1 and Figure 4 that was established prior to the actual loadings from previous experience with docks and the literature. Thus, an observational approach was adopted at the prototype stage with controls on monitored behaviour that would yield the necessary information, particularly pore pressure response, to consider increased future loadings. Close interaction between field staff (Sault Ste Marie), and engineering and analysis staff (Toronto/Hamilton), was established so that the controls and safety factors could be upgraded following monitoring for each load increment. The contingency plan was simple: diversion of the next ship or rapid unloading if critical.

The test loading plan, profile and inclinometer response at the location with greatest lateral movement are shown in Figure 5. Test loading consisted of placing a 26 m high pile of limestone over three days (4 ship loads totalling 70,000 t) which generated pore pressures in the varved clay of up to 0.73 times the applied pressure (Figure 6A), maximum lateral movements of 13 mm (Figure 5C), and stress relaxation in the anchor rod of up to 55 MPa that decreased with time. Pore pressures dissipated by 50 per cent of maximum observed values within one month and this is significant in terms of repetitive loading and future loading plans.



A. CROSS SECTION – STEEL SHEET PILE EXTENSION (STA. 1+60)

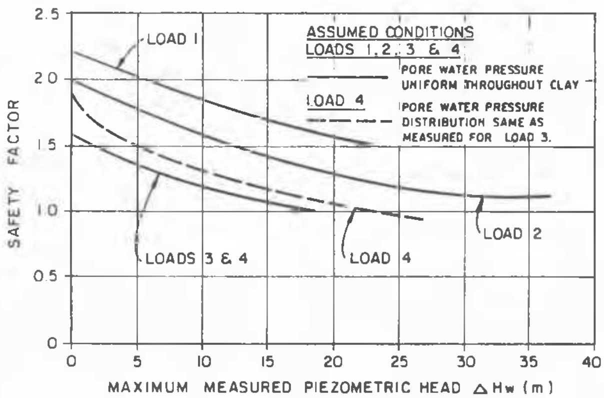
MATERIALS	γ kg/m³	γ' kg/m³	ϕ' (DEGREES)
LIMESTONE	1442 ■	–	38 ■■
FILL	1874	881	30
SAND	1874	881	35
CLAY	1794	801	25
SILT	1954	961	40
TILL	2195	1201	40
ORE (TILDEN)	2387	–	26

■ — 1923 kg/m³ ASSUMED FOR PROPOSED TEST LOAD
■■ — 40° ASSUMED FOR PROPOSED TEST LOAD
ZERO EFFECTIVE COHESION ASSUMED FOR ALL MATERIALS

APPROXIMATE SAFETY FACTORS

	r_u=0.0	r_u=0.2	r_u=0.4	r_u=0.6
LOAD 1	2.2	2.0	1.7	1.4
LOAD 2	1.9	1.6	1.3	1.1
LOAD 3	1.6	1.3	1.1	0.9
LOAD 4	1.5	1.2	1.0	0.8

TYPICAL FAILURE SURFACES – LOAD INCREMENT 2



B. PORE PRESSURE CONTROL GRAPHS

Fig. 4 Proposed Test Load Stability Analyses And Piezometer Response Control

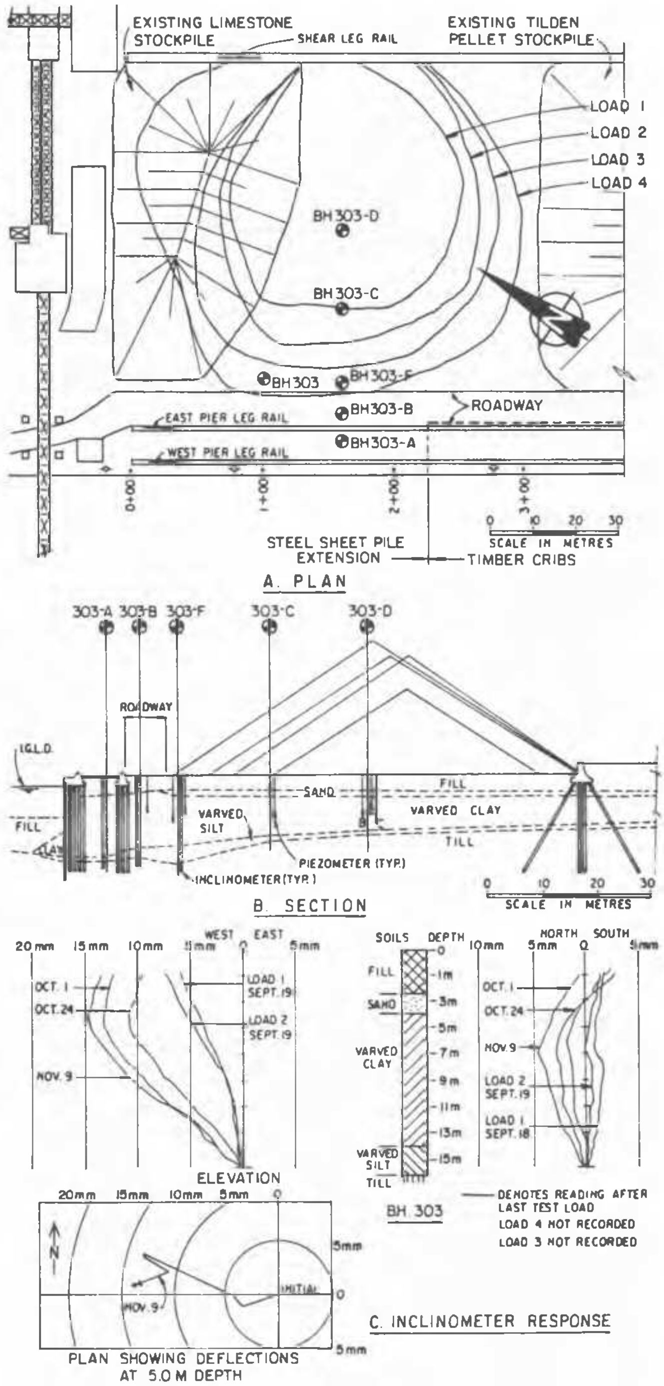


Fig. 5 Test Loading and Inclinometer Response

TABLE 1

INSTRUMENTATION RESPONSE CRITERIA

INSTRUMENTATION	RESPONSE*			
	ALL GO	CAUTION	OFFICE ANALYSIS	CRITICAL (Unload)
INCLINOMETER	<50 mm	50 mm	100 mm or one difficult to read	>150 mm or too difficult to read or acceleration after 50% of load increment
ALIGNMENT				
- Stakes	<25 mm	25 mm	50 mm	>75 mm
- Brass Plugs	<13 mm	13 mm	25 mm	>38 mm
ELEVATIONS	--	--	--	>13 mm upward
EXTENSOMETERS	--	--	one rod of pair yielding	two rods of pair yielding
PIEZOMETERS (Figure 4)	1.2 FS	1.2 FS	1.1 FS	<1.05 FS

* Response:

All Go - proceed without direction from Toronto, report daily.

Caution - permission to proceed required from Toronto, report daily.

Office Analysis - immediate report required, permission to place next load must be obtained from Toronto.

Critical - field decision to immediately remove load, immediate report to Toronto.

FS = Factor of Safety.

Effective stress stability analyses (Morgenstern and Price) based on the monitored pore pressure indicated a minimum safety factor of approximately 1.2 during test loading (Figure 6B) that would decrease to less than unity if the proposed 20.7 m high ore pile full loading was applied. The shear resistance contribution from the bulkhead structure was not considered in these analyses. (Since the berth depth had already been increased up to 1 m by scour, this parameter was no longer involved.) Precise surveying during test loading, such as time-alignments (Figure 3), were over a short time period compared to the overall time scales of concern.

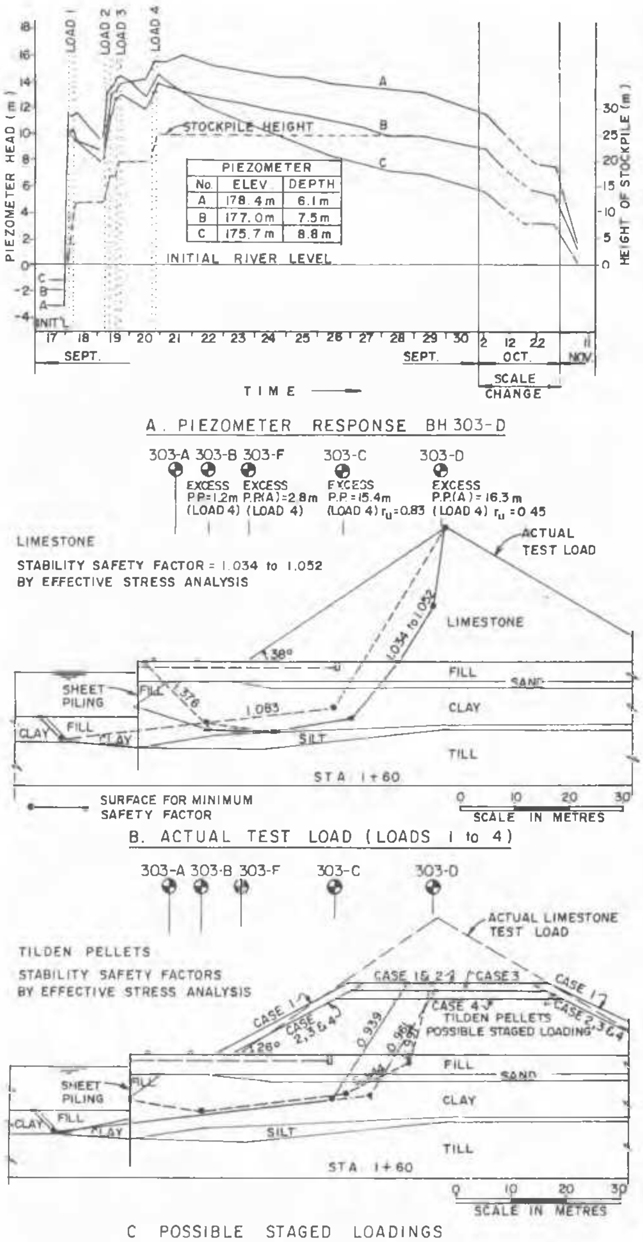
While elastic analyses are not fully applicable for the soils involved, elastic finite element analyses, based on measured moduli where available from pressuremeter testing, were used to study deformation trends(Figure 7). These provided a valuable insight into the anticipated dock response during test loading, and were found to both parallel the observed behaviour and indicate relaxation of the anchor rods. The monitored and computed deformation levels were comparable, and indicated that essentially elastic responses were involved (i.e., low strain levels) rather than plastic and creep deformations.

STAGED LOADING

The test loading programme indicated that the full loading could not be applied without some strength improvement in the varved clay. Also, a review of the laboratory data, soil response and technical literature, indicated that while incremental lateral spreading would continue, strain softening and incremental pore pressure build up due to repetitive loading would not be a problem. On this basis, and using the monitored pore pressure response, the possible staged loading strategy in three increments over one year given on Figure 6, with detailed monitoring control was recommended. It should be noted that in the analyses summarized on Figure 6, there is no shear resistance contribution from the bulkhead structure and the potential strength improvement in the varved clay is also neglected. Obviously, the safety factors involved will be somewhat greater than unity when these factors are considered.

CONCLUSION

It was concluded that: the test loading applied a greater pressure on the varved clay than any previous loads; stage loading could increase the strength of the varved clay within one year so that full ore pellet loading could be applied; stage loading would initially cause relaxation of anchors; and, significant lateral movements of the structure and settlements of the ore yard would follow, resulting in increased anchor stresses within acceptable limits. The overall test loading programme indicated that such dock structures can be operated at low safety factors (i.e., 1.1 to 1.2 acceptable) and tolerate relatively large deformations.



CASE 1 4.6 m ROAD, 12.2 m HIGH S.F.= 0.939
CASE 2 7.6 m ROAD, 12.2 m HIGH S.F.= 0.944
CASE 3 7.6 m ROAD, 10.7 m HIGH S.F.= 0.961
CASE 4 7.6 m ROAD, 9.1 m HIGH S.F.= 0.977
BY EFFECTIVE STRESS ANALYSIS

CASE 1, CASE 2, CASE 3&4 — SURFACES FOR MINIMUM SAFETY FACTORS

Fig. 6 Piezometer Responses and Stability Analyses

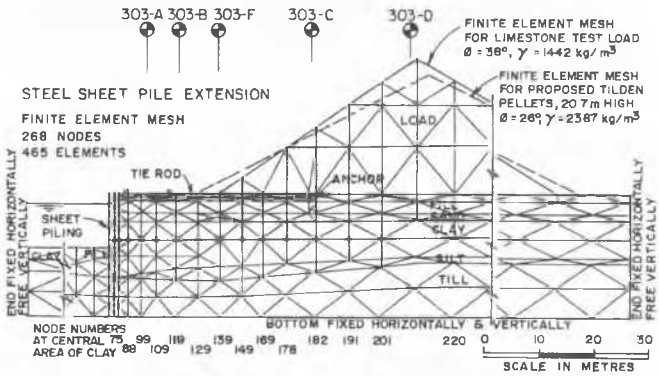


Fig. 7 Finite Element Method Mesh

ACKNOWLEDGEMENT

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