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# Measurements with Wiegmann Inclinator on Five Sheet Pile Bulkheads

## Mesures avec l'Inclinomètre Wiegmann sur Cinq Quais en Palplanches

by G. P. TSCHBOTARIOFF, Dr. Ing., Professor of Civil Engineering, and E. R. WARD, C.E., Research Associate, Princeton University, Princeton, New Jersey, U.S.A.

### Summary

This paper describes five bulkheads in the harbours of New York, Galveston, Baltimore and Cleveland on which measurements were performed with the Wiegmann Inclinator. Bending moments thus determined in the steel sheet piling of these bulkheads are compared with moments computed by two of the existing theories.

### Introduction

The research described in this paper was sponsored by the Geophysics Branch, Office of Naval Research, Department of the Navy, Washington, D.C.

The Wiegmann Inclinator permits slope measurements on steel piling to an accuracy of 1 in 10,000. Its construction and the first measurements in the Harbour of Bremen are described by WIEGMANN, 1953 and 1954.

A Wiegmann Inclinator was acquired by The Eugene Higgins Fund of Princeton University in 1954. Its performance was checked on a 32 ft. long H pile (14WF30) set up vertically and loaded horizontally (TSCHBOTARIOFF *et al.*, 1955).

Typical steps in the performance check are shown in Fig. 1.

### Sommaire

Cet exposé décrit cinq quais des ports de New York, Galveston, Baltimore et Cleveland et les mesures qui y furent exécutées à l'aide de l'Inclinomètre Wiegmann. Les moments fléchissants déterminés par cette méthode dans les palplanches métalliques de ces quais sont comparés avec les moments calculés selon deux des théories existantes.

All three zero load runs disclosed slight undulations of the pile presumably caused by eccentricities of rollers in the mills. Fig. 1 also indicates the results obtained by applying concentrated loads at third points. If the measured slope readings are corrected for the zero load readings, they coincide almost exactly with the actual (i.e. theoretical) curve. It is then possible to proceed as was done by WIEGMANN (1953 and 1954), i.e. to differentiate the smoothed-out slope curve to obtain the bending moment curve, then by repeating this procedure, obtain the shear curve and the load diagram. Without zero load corrections the bending moment curve is insufficiently accurate to permit further differentiation. The maximum

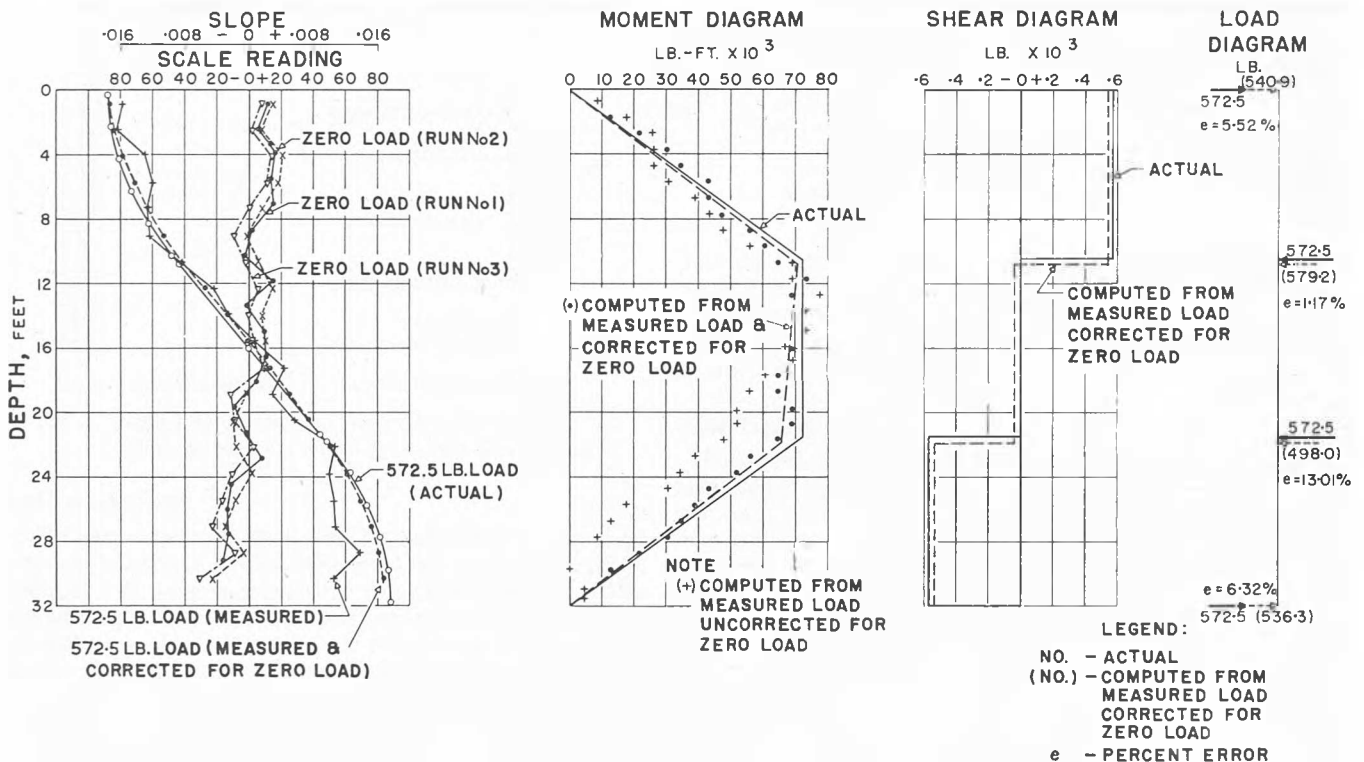


Fig. 1 Performance check of Wiegmann Inclinator on a steel H pile  
Contrôle de comportement de l'Inclinomètre Wiegmann à l'aide d'un pieu 'H' en acier

value, however, agrees within some 10 per cent with the theoretical maximum bending moment.

Since no new anchored bulkhead construction was under way where zero load readings could be taken, it was decided to carry out a survey of existing bulkheads within the United States to ascertain order of magnitude of bending moments in the steel sheet piling under varying field conditions.

The survey was made with the help of an announcement in *Newsletter*, Soil Mechanics Division, American Society of Civil Engineers, of the Bethlehem Steel Company and of the United States Steel Corporation. Only a surprisingly small number (ten) of bulkheads possibly suitable for study was found. The measurements on five bulkheads with the most reliable and comprehensive results are reported in this paper. These bulkheads will be referred to by the letters A, B, C, D and E. Their locations are:

**Bulkhead A**—Pier at foot of 36th Street, Brooklyn, New York Harbour (see Figs. 2 and 3 and TSCHEBOTARIOFF *et al.*, 1955).

**Bulkhead B**—Pier 39, Galveston Wharves, Galveston, Texas (see Figs. 4 and 5 and TSCHEBOTARIOFF *et al.*, 1956).

**Bulkhead C**—Pier 35, Galveston Wharves, Galveston, Texas (see Figs. 6 and 7 and TSCHEBOTARIOFF *et al.*, 1956).

**Bulkhead D**—Baltimore and Ohio Railroad Ore Dock, Baltimore, Maryland (see Figs. 9 and 10 and TSCHEBOTARIOFF *et al.*, 1956).

**Bulkhead E**—Dock of the Cleveland Builders Supply Co., on the Cuyahoga River, Cleveland, Ohio (see Figs. 11, 12 and 13 and TSCHEBOTARIOFF, 1956).

Prior to actual measurements, the sheet piles on all bulkheads were inspected underwater and cleaned of marine growth by the senior author and by his assistant, Mr. E. DiBiagio, using an open-helmet diving apparatus and a platform lowered by a crane.

Laboratory soil test data was available only for Bulkheads B and C. Soil samples were available for Bulkhead A. Borings were performed with research project funds to obtain soil samples from Bulkheads D and E. They were all tested in the Soil Mechanics Laboratory, Princeton University. The soil test data for all bulkheads are given in Table 1.

## Bulkhead A

Built in 1952, using 65 ft. long ZP-38 steel sheet piles ( $I = 281 \text{ in.}^4/\text{ft. wall}$ ;  $S = 46.8 \text{ in.}^3/\text{ft. wall}$ ) for 35 ft. of water

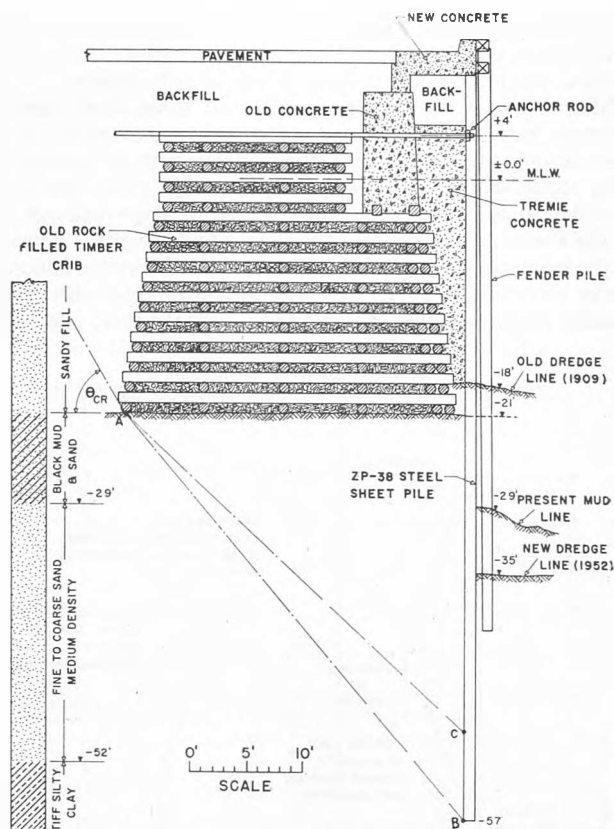


Fig. 2 Cross-section of bulkhead A  
Coupe transversale du quai A

and 12 ft. of freeboard. Critical slippage surfaces could not intersect the crib and therefore had to pass through point A at the lower inside corner of the old (1909) crib (Fig. 2). Above

Table 1  
Soil properties\*

Bulkhead	See profile on Fig.	Elevation (ft.)		Blows per ft.†	Consistency limits (%)			w (%)	$\sigma_f$ ton/sq. ft.	Unit dry weight (lb./cu. ft.)
		From	To		LL	PL	PI			
A	2	-29	-52	10-16	Non-plastic sand			25-32	1.80	94-103
		-52	-112	5-12	31-36	20-24	11-12			
B	4	-30	-48	?	50-90	?	?	26-36	1.1-1.9	85-97
		-48	-64	?	?	?	?	26-36	1.4	89-98
D	10	0	-8	3-5	43-49	27-32	16-17	40-41	0.4	84-89
		-8	-16	2-4	78-82	31-44	38-47	44-65	1.3-1.8	64-83
		-16	-33	4-23	Non-plastic silty sand			—	—	—
		-33	-43	23-292	Non-plastic silty sand			—	—	—
		-43	-48	41-185	41	19	22	?	?	?
		-48	-61	140-324	Non-plastic silty sand			—	—	—
E	13	-3	-17	2-6	Non-plastic silty sand			—	—	—
		-17	-19	2-3	32	29	3	39	0.3	84
		-19	-21	2-3	Non-plastic silty sand			—	—	—
		-21	-26	4-10	Non-plastic silty sand			—	—	—
		-26	-36	10-43	Non-plastic silty sand			—	—	—
		-36	-41	26-38	28	19	9	23	0.5	100
		-41	-56	16-52	27-29	18-22	6-11	22-25	1.9-2.8	106-111

\* Minimum (10) and maximum (16) values indicated thus: 10-16

† 140 lb. hammer; 30 in. drop; 2.0 in. O.D. and 1.5 in. I.D. split spoon sampler

that point their inclination was computed in the conventional manner. Below the crib the failure surface had to pass through point B at the tip of the sheet piling for computations by the 'free earth support' method, and through point C for the assumption of a 'hinge' at or above the dredge line. On the basis of previous Princeton model tests (TSCHEBOTARIOFF, 1951) point C was located at 2/3 of the depth of embedment.

Measurements were made in 1954 on three sheet piles at different locations: 1, 2 and 3. The bending moment curves were computed from slope curves representing an average of three separate runs of slope readings on each pile. Each run provided some 70 photographically recorded slope readings, i.e. on the average a reading for every 6 in. of pile height. Because of the uncertain degree of interaction between tremie concrete above elevation - 18 ft. and the adjoining sheet piling, the bending moment curves shown on Fig. 3 for the three piles were

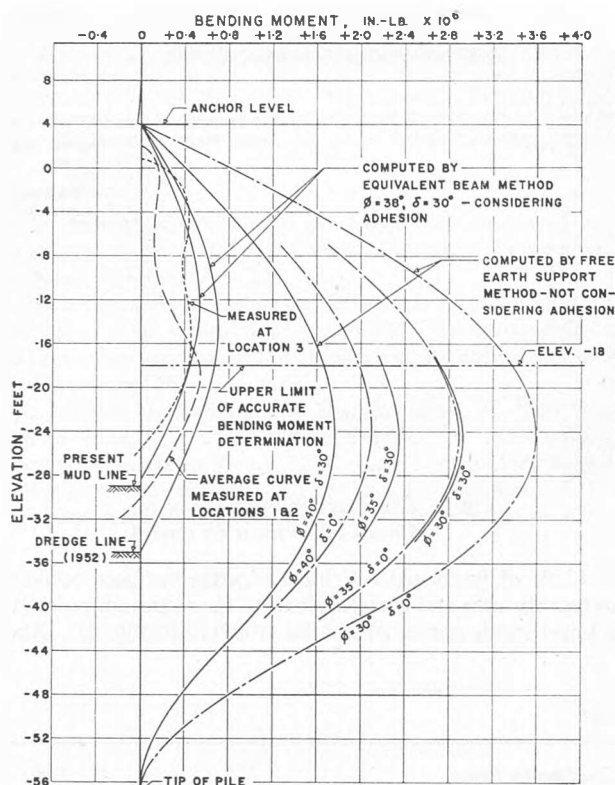


Fig. 3 Bulkhead A. Comparison of measured and of computed bending moments

Quai A. Comparaison des moments fléchissants mesurés et calculés

computed from slope readings using the moment of inertia of the steel sheet piling alone. This is correct only below elevation - 18 ft. Nevertheless, it can be seen from Fig. 3 that the point of zero bending moment—the 'hinge'—is located well above the dredge line; that the measured curves below elevation - 18 ft. agree very well with a theoretical curve for  $\phi = 38$  degrees,  $\delta = 30$  degrees and the actual location of the 'hinge', also that the average actual maximum bending moment does not exceed 25 per cent of the theoretical 'free earth support' value for  $\phi = 38$  degrees,  $\delta = 30$  degrees. The actual bending stress in the sheet piling does not exceed 11,350 lb./sq. in.

#### Bulkhead B

Built in 1954, using 65 ft. long Hoesch IV steel sheet piles ( $I = 215$  in.<sup>4</sup>/ft. wall;  $S = 40.9$  in.<sup>3</sup>/ft. wall) for 32 ft. of water and 10.5 ft. freeboard. Replaced previously existing creosoted

timber pier (25 ft. of water) which had been damaged by marine borers. Old timber piles were then either pulled or broken off at previously existing sloping soil surface (Fig. 4).

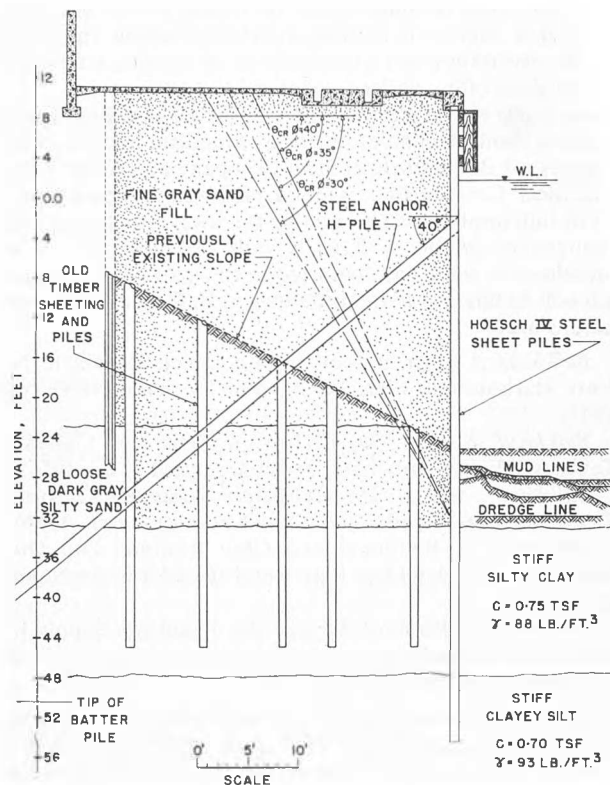


Fig. 4 Cross-section of bulkhead B  
Coupe transversale du quai B

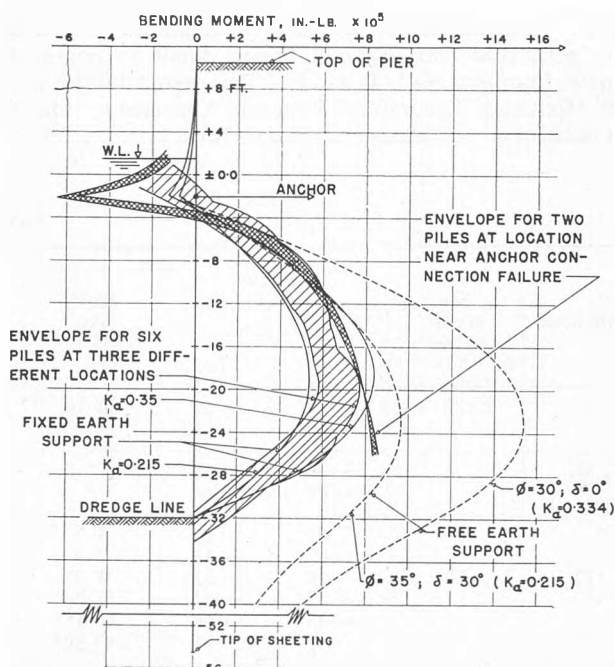


Fig. 5 Bulkhead B. Comparison of measured and of computed bending moments

Quai B. Comparaison des moments fléchissants mesurés et calculés

Slope measurements were performed in 1955 on eight sheet piles at four different locations. At least two measuring runs were made on each pile and the results averaged.

Theoretical bending moment curves for two assumptions—of 'free earth support' and of 'hinge at dredge line'—are shown on Fig. 5. A uniform resistance along the entire depth

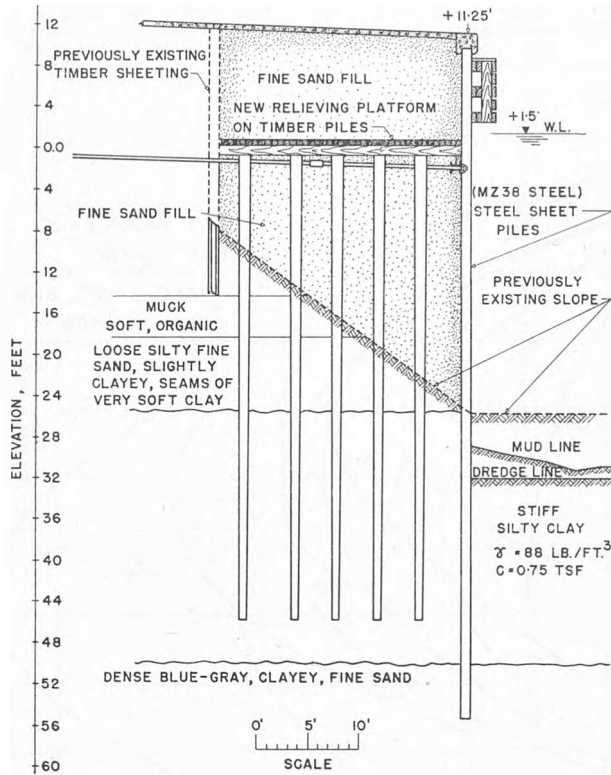


Fig. 6 Cross-section of bulkhead C  
Coupe transversale du quai C

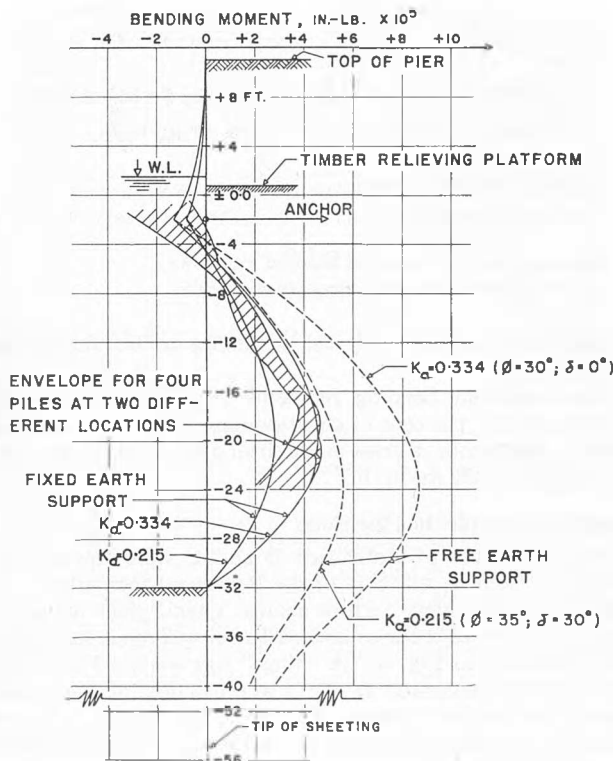


Fig. 7 Bulkhead C. Comparison of measured and of computed bending moments  
Quai C. Comparaison des moments fléchissants mesurés et calculés

of sheet pile embedment—of an intensity sufficient to balance the active pressures around the anchor—was used for the free earth support computations.

The envelope of the bending moment curves computed from actual slope measurements on six piles at three locations closely

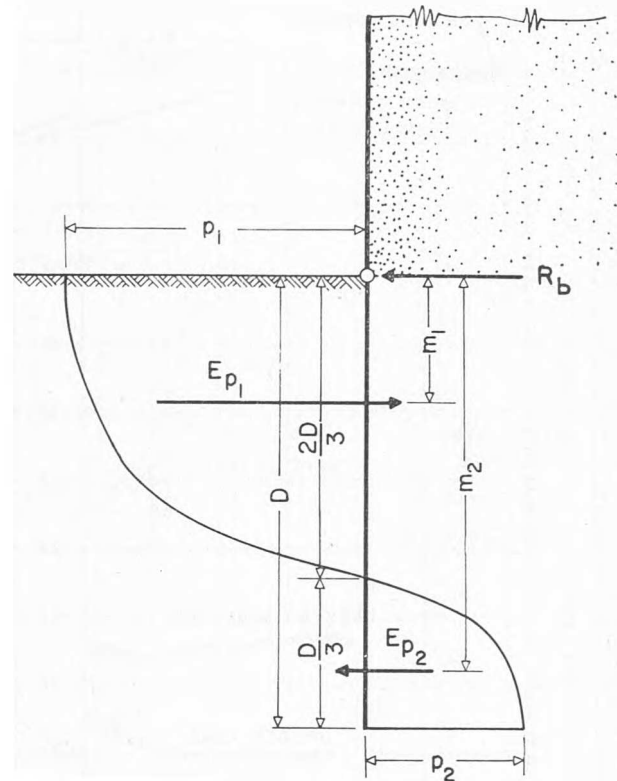


Fig. 8 Bulkheads B and C. Computation of safety factors for sheet pile fixation in clay

Quais B et C. Calcul des facteurs de sécurité de l'encastrément des palplanches dans l'argile

agrees with the limits of the 'hinge at dredge line' theoretical curves (Fig. 5). The maximum bending moments of these latter curves equal 53 per cent of the corresponding 'free earth support' values. The bending stress in the sheet piling as measured does not exceed 19,000 lb./sq. in.

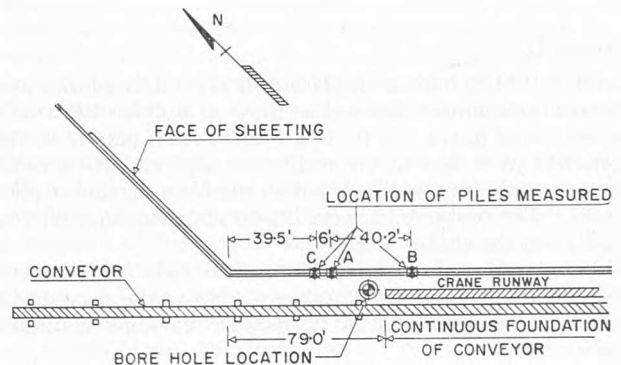


Fig. 9 Bulkhead D. General plan  
Quai D. Plan d'ensemble

An exception is presented by two piles near the place where several chain links connecting the H-batter pile to the sheeting broke and had to be repaired. This somewhat overloaded the two piles measured at that location (Fig. 5).

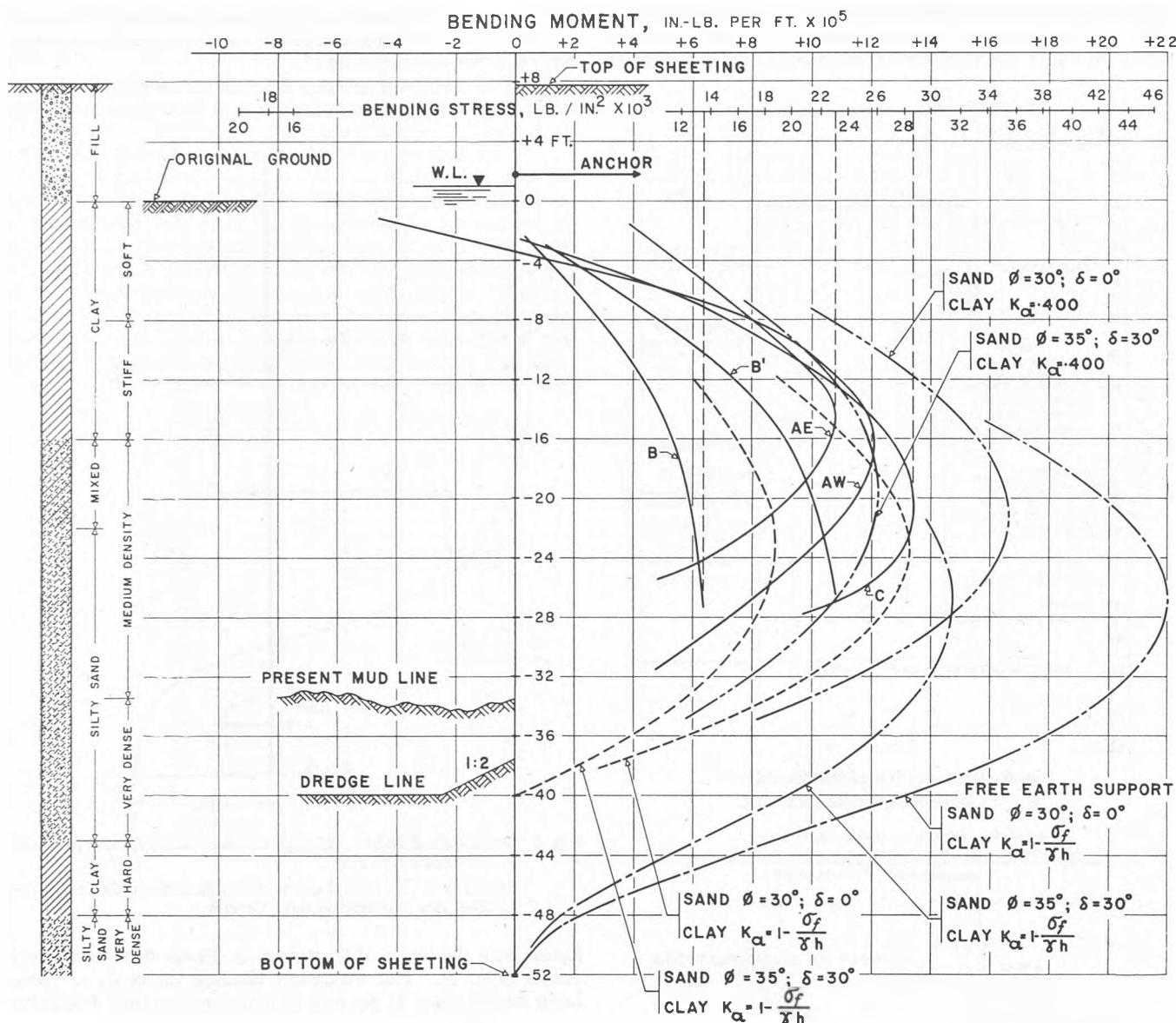


Fig. 10 Bulkhead D. Soil profile and comparison of measured and of computed bending moments  
Quai D. Coupe du terrain et comparaison des moments fléchissants mesurés et calculés

### Bulkhead C

Built in 1951 to replace an old timber pier under general and soil conditions almost identical to those of Bulkhead B except that somewhat heavier 65 ft. long MZ-38 sheet piles ( $I = 281$  in.<sup>4</sup>/ft. wall;  $S = 46.8$  in.<sup>3</sup>/ft. wall) were used and active earth pressures were decreased by a timber platform on timber piles (Fig. 6). The timber piles were driven after the sand fill was placed up to the anchor level.

Slope measurements were performed in 1955 on four steel sheet piles at two different locations. No readings could be taken below elevation -24 ft. because of some coral-like growth.

The envelope of the bending moment curves computed from the measured slopes using the moment of inertia of steel sheeting only again fell within the limits of the 'hinge at dredge line' theoretical curves (Fig. 7) as it did for Bulkhead B (Fig. 5). The agreement is probably accidental. It would appear that the 7 ft. dredging after completion of the pier produced deformations which were sufficient to relieve the 'wedging in' effects of the fill due to timber pile driving but which were not large

enough to bring into play the resistance to bending of the timber piles.

The maximum bending moments of 'dredge line hinge' curves equal 51 per cent of corresponding 'free earth support' values. The bending stress in the sheet piles, as measured, does not exceed 10,200 lb./sq. in.

### Sheet Pile Fixation in Clay Soils

The sheet piles of Bulkheads B and C were found to be effectively fixed in stiff clay of the Beaumont formation. An estimate of the safety factors against lateral yield of clay at dredge line due to shear or consolidation was made as follows, with reference to Fig. 8. A 'hinge' was assumed at dredge line;  $R_b$  was computed as the lower reaction of 'equivalent beam'; the active pressures of clay below dredge line were ignored as a first approximation, since vertical pressure there  $\gamma H = 2870$  lb./sq. ft. is smaller than  $2c = 3000$  lb./sq. ft.  $= \sigma_f$  and since old timber piles are present. Then:

$$E_{p1} - E_{p2} = R_b \quad \dots (1)$$

$$(E_{p1} \times m_1) = (E_{p2} \times m_2) \quad \dots (2)$$

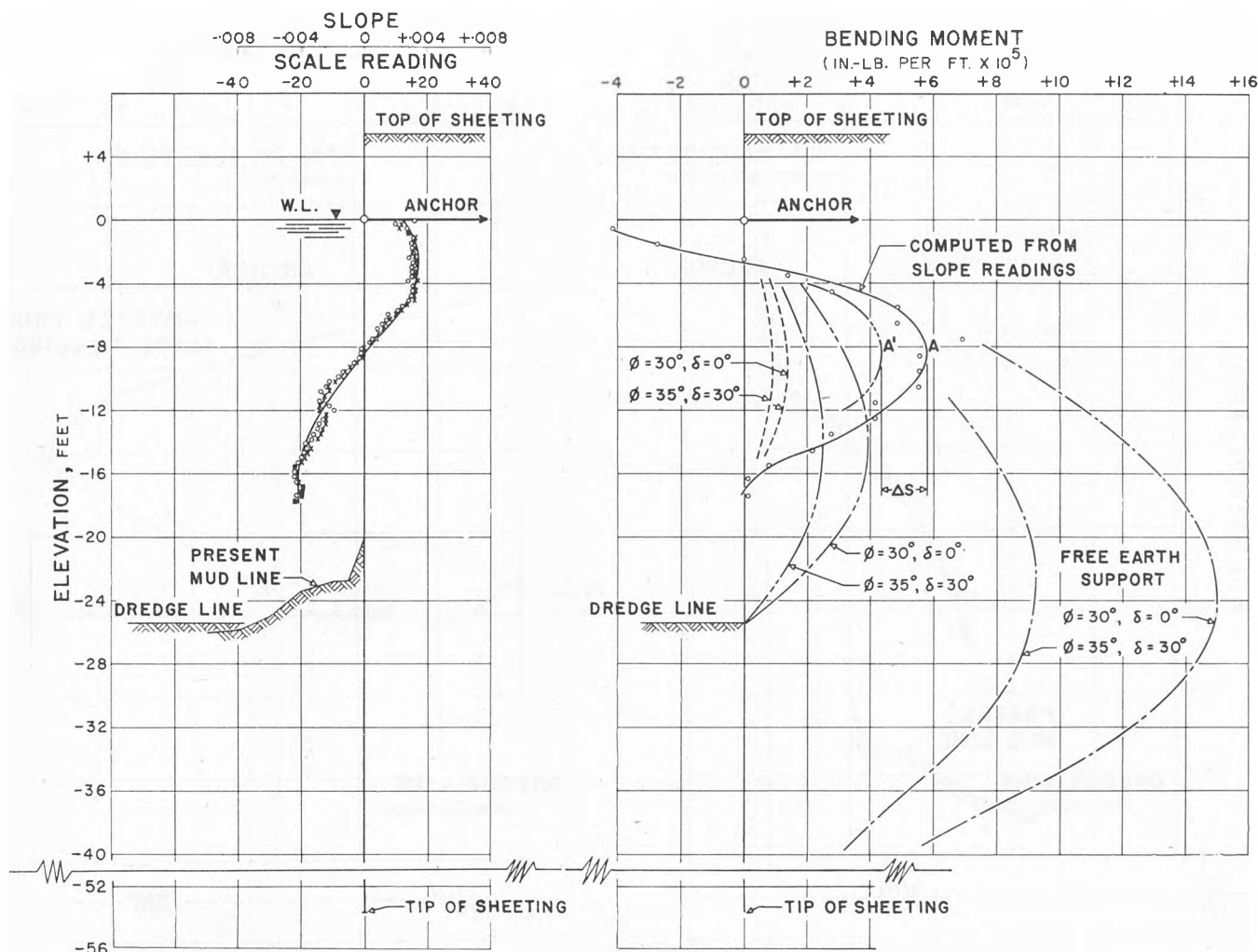


Fig. 11 Bulkhead E; sheet pile A. No surcharge. Slopes and bending moments measured and computed  
Quai E; palplanche A. Pas de surcharge. Inclinaisons et moments fléchissants, mesurés et calculés

It was assumed that passive resistance pressures vary parabolically and change sign at  $2/3D$ ; then, from equations 1 and 2:

$$p_2 = 0.57p_1 \quad \dots (3)$$

$$p_1 = 3.15(R_b/D) \quad \dots (4)$$

For Bulkhead B:  $p_1 = 720$  lb./sq. ft. and for Bulkhead C:  $p_1 = 410$  lb./sq. ft.

Safety factor against shear:

$$F = (2c)/p_1 \quad \dots (5)$$

With  $2c = 3000$  lb./sq. ft., for Bulkhead B:  $F = 4.17$ ; and for Bulkhead C:  $F = 7.3$ .

Further, if we assume that  $(c/p_c) = 0.35$  for this clay, a conservative value of the vertical pre-consolidation pressure  $p_c = 2.25$  ton/sq. ft. is obtained. Assuming that the horizontal value  $p_{ch}$  is one-half of the vertical  $p_c$ , we find that for Bulkhead B:  $(p_1/p_{ch}) = 0.32$  and for Bulkhead C:  $(p_1/p_{ch}) = 0.18$ . No appreciable additional lateral consolidation was therefore to be expected nor were any effects thereof observed.

#### Bulkhead D

Built in 1950, using 60 ft. long MZ-38 steel sheet piles ( $I = 281$  in.<sup>4</sup>/ft. wall;  $EI = 8284 \times 10^6$  lb. in.<sup>2</sup>/ft. wall;  $S = 46.8$  in.<sup>3</sup>/ft. wall) for 40 ft. water and 8 ft. freeboard. The reinforced concrete crane runway (Fig. 9) formed an integral

part of the sheet pile cap and was supported every 5 ft. by four Monotube Type JN-14, No. 7 gauge piles, 50 ft. long, reaching down to elevation  $-49.7$  ft; ( $EI$  of steel shell plus concrete cracked in tension zone =  $5911 \times 10^6$  lb. in.<sup>2</sup>/ft. wall).

Slope measurements were made in 1955 on four sheet piles at three different locations with at least two runs on each pile. One pile (location B) was in the crane runway section, the two piles—AE and AW—(location A) and one pile (location C) were 33.5 ft. and 39.5 ft. away from the crane runway and its Monotube Piles (Fig. 9).

The bending moment curves computed from slope measurements on piles C, AE and AW agree best with the 'hinge at dredge line' theoretical curves (Fig. 10). The maximum bending moments of these latter curves equal 61 per cent of the corresponding 'free earth support' values. There is no marked difference in this case between theoretical curves based on 'strength theory'  $K_a = (1 - \sigma_f/\gamma h)$  and on the 'neutral' theory ( $K_0 = 0.400$ ) (see TSCHEBOTAROFF, 1951). The bending stress as measured in the sheet piling does not exceed 28,700 lb./sq. in. (pile C).

The maximum stress as measured in the sheet piling at location B does not exceed 13,500 lb./sq. in. This indicates that the Monotube Piles fully participate in resisting bending presumably due to large deformations induced by dredging 40 ft. from original ground level after completion of bulkhead and of crane runway construction. Curve B' in Fig. 10 was

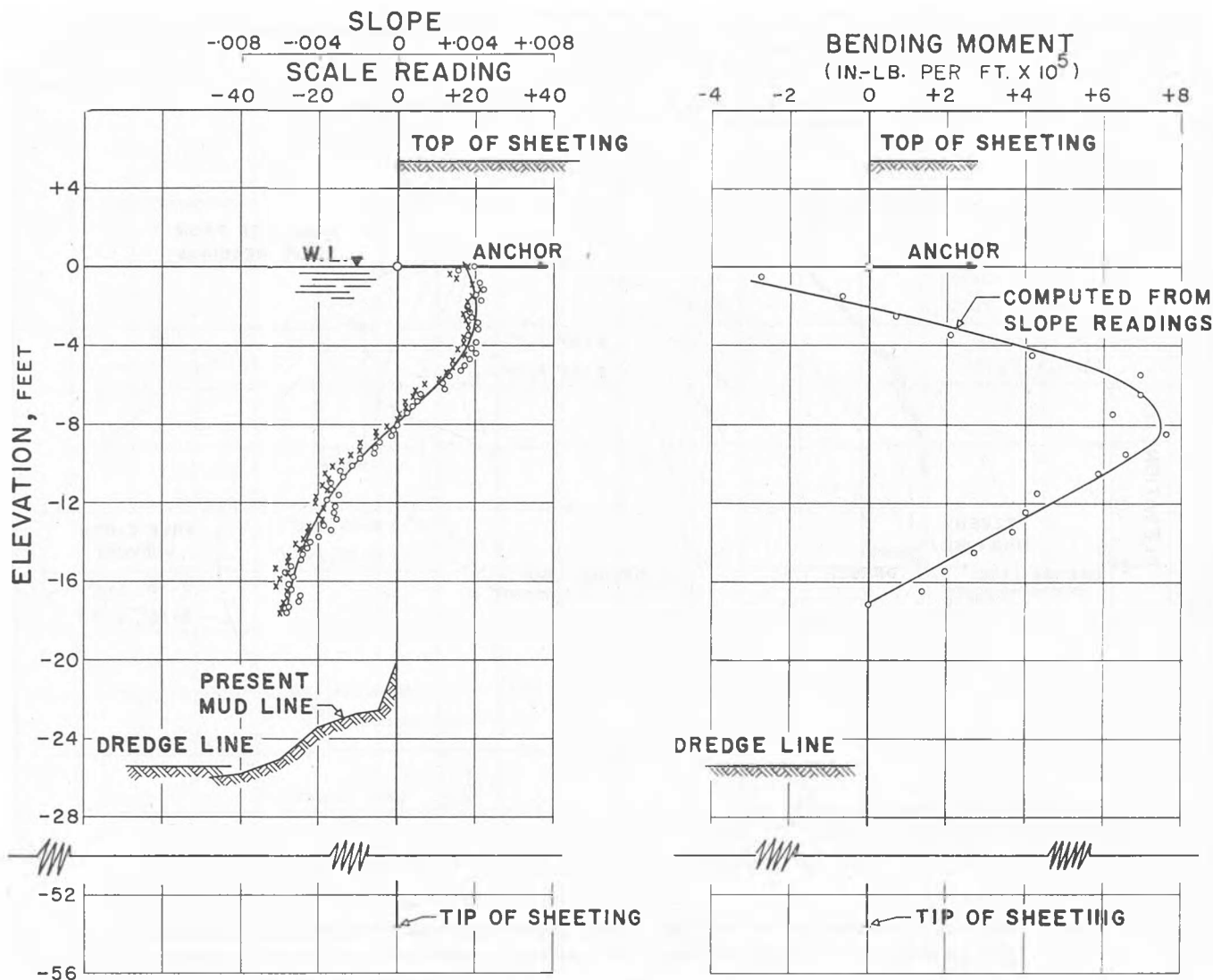


Fig. 12 Bulkhead E; sheet pile A. 4200 ton surcharge load. Measured slopes and bending moments  
Quai E; palplanche A. Surcharge de 4200 tonnes. Inclinaisons et moments fléchissants mesurés

obtained by using the  $EI$  values of the steel sheeting plus the  $EI$  values of the Monotube Piles.

#### Bulkhead E

Built in 1954, using 60 ft. long MZ-38 sheet piles ( $I = 281$  in.<sup>4</sup>/ft. wall;  $S = 46.8$  in.<sup>3</sup>/ft. wall) for 24 ft., water and 6 ft. freeboard. The unusually large embedment  $D = 30$  ft. = 0.5 of total length of sheet piles was provided in view of heavy surcharge loads—stockpiles of sand, gravel and crushed stone.

Slope measurements performed in 1955 included one sheet pile at each of two locations—A and C—just before and after a heavy surcharge load. Fig. 11 shows the slope curve for two measurement runs (circles and crosses for the respective readings) at location A and the bending moment curve computed from the smoothed-out slope curve, for the condition when all surcharge had been removed for at least two weeks from dock surface within 100 ft. of piles A and C. Two days later 4200 tons of crushed stone rising from the edge of the dock to 28 ft. height was placed within a few hours by self-unloading belt conveyer ship. The two runs of slope measurements at location A and the computed bending moments after that surcharge was in place for two days are shown on Fig. 12.

Figs. 11 and 12 show that the zero bending moment—the

'hinge'—is 7 ft. above dredge line. This is to be attributed to considerable depth of embedment.

Almost identical results were obtained on pile C. The maximum bending moment increment values ( $\Delta S$ ) agree well with value computed for that surcharge cone by use of Newmark's chart. This was done without considering the doubling 'mirror image' effect (TSCHEBOTARIOFF, 1951). If that effect is taken into account by subtracting  $\Delta S$  from the 'no surcharge' curve A, Fig. 11, the maximum bending moment curve A' will equal 47 per cent of 'free earth support' value and will closely agree with 'hinge at dredge line' value for  $\phi = 30$  degree,  $\delta = 0$  degree, but will still be three times greater than the corresponding value for the actual 'hinge' location. The actual  $K_a$  value therefore is close to unity, presumably due to the very loose nature of the sand (Fig. 13) which was 'wedged' behind the sheet piling by nine successive surcharge loadings since the bulkhead construction. The maximum stress measured in the sheet piling at 'A' and 'C' does not exceed 16,000 lb./sq. in. under full surcharge load.

#### Conclusions

Maximum bending moments computed for assumed 'hinge at dredge line' of five bulkheads reported on closely agree with

