Base of the extracted pile No. 10.

FIG. 24

Base of the extracted pile No. 11. Note on the left the grouting pipe.

FIG. 25

the design of pile foundations.

REFERENCES.

1) a - Santarella "Tecnica delle fondazioni", Ed. Hoepli, Milan.
b - Catalogue "Pieux Rodio", de la société SEC, Paris
c - Note sur les travaux de réparation du Pont du Portail sur la Seille. Wahl et Dondin, 1937. Annales de la voirie, mai.
d - "La Gare Maritime d'Oran" revue "Chantiers" janv. mars 1936.
e - Electrification de la ligne du Mans. M. Laborde Science et Industrie - "Electricité" juin 1937
f - Parois de pieux jointifs, Travaux déc. 1941.
2) "Etude expérimentale de la force portante d'un pieu foré" H. Cambefort ("Travaux", juillet/août 1947).

-o-o-o-o-o-o-

VII a 10

PERFORMANCE OF PILE FOUNDATIONS OF NAVIGATION LOCKS AND DAMS ON THE UPPER MISSISSIPPI RIVER

LAWRENCE B. FEAGIN

Head Engineer, St. Louis District,
Corps of Engineers, Department of the Army, St. Louis, Mo., U. S. A.

SUMMARY

From 8 to 12 years have elapsed since completion of the navigation locks and dams on the upper Mississippi River, thereby affording an appreciable period for observing movement of those structures founded on piles. Records of such observations are presented for selected representative locks and dams, and comparisons are made with the results of pile driving and load tests made during construction.

Description of Project. The Congress of the United States, by an act approved by the President on July 3, 1930, authorized the improvement by the Corps of Engineers, United States Army, of some 650 miles of the upper Mississippi River to provide a navigable channel with minimum depth of 9 feet and width of 300 feet. The improvement was accomplished by construction of 23 locks and dams in addition to 3 previously completed. The last was placed in operation in 1940.

The locks are 110 ft. wide by 600 ft. long with provision for a future auxiliary lock at most projects. At Alton the auxiliary lock, 110 ft. by 360 ft., was provided initially. Most of the dams consist of various combinations of tainter and roller gates separated by concrete piers. Sills are at approximately river bed level.

Of the 26 locks and dams, 22 are founded in whole or in part on piles. The maximum lift for these 22 locks ranges from 5.5 to about 25 ft. (See Fig. 1)

Foundations. With few exceptions the pile foundations are in deep deposits of sand, vary-

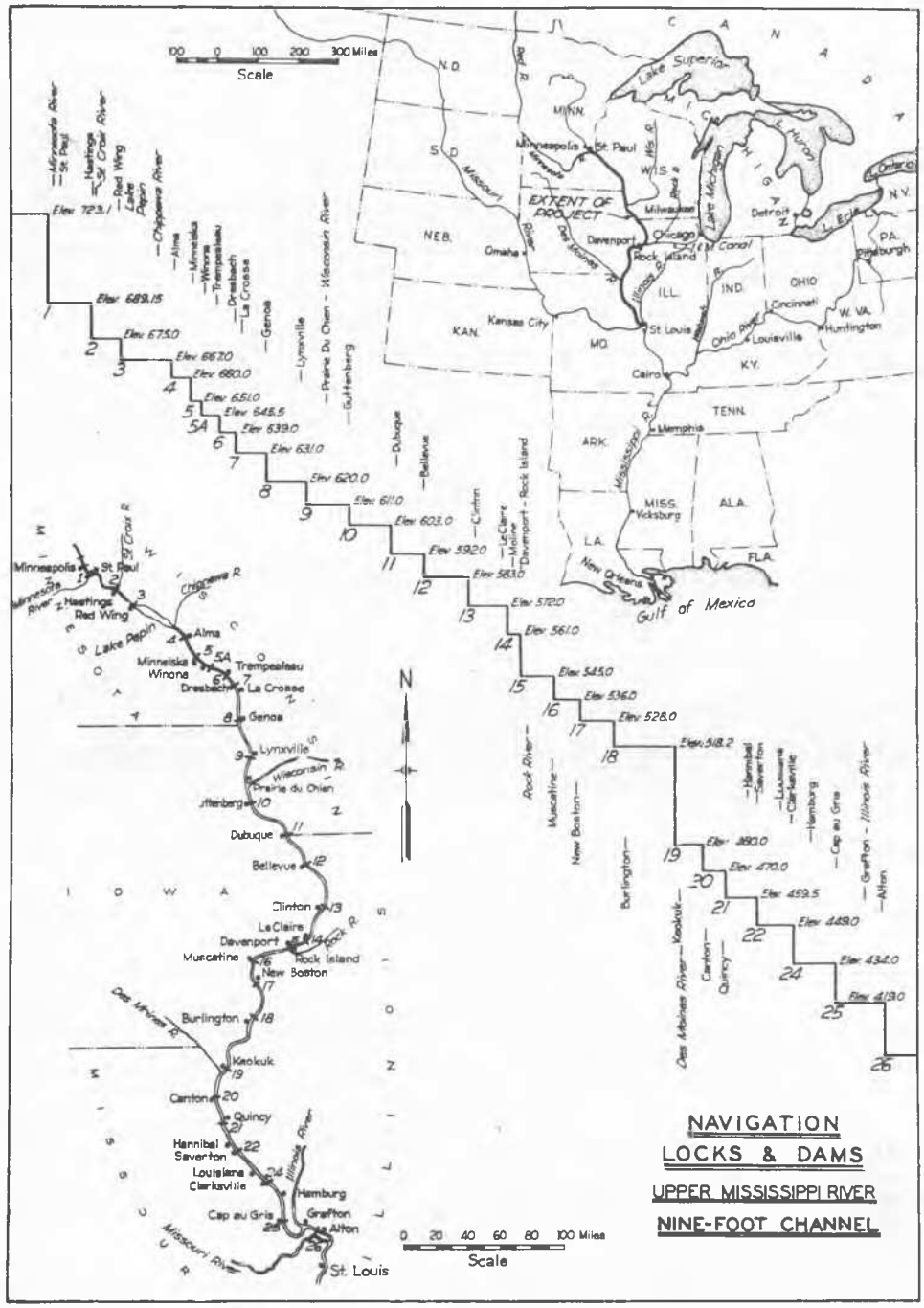


FIG. 1

ing from fine to coarse, occasionally mixed with small percentages of gravel. At certain sites, silt and clay presented special problems.

Design Criteria. In general, foundations were designed on the assumption that timber piles could support a maximum vertical load of 25 tons per pile and concrete piles 50 tons per pile with a minimum spacing of 3 ft. on centers. Lateral loads were limited to about 4 tons per pile. Batter piles were used only for special conditions. Allowable lateral movement or vertical settlement was assumed to be 0.02 ft. (1/4 in.)

Load Tests. At the beginning of construction at each site, appropriate pile lengths were determined by load tests on individual piles of various lengths at representative locations, and in some instances on small groups of piles. Maximum vertical loads at least double and sometimes triple the design load were applied and usually sustained until further settlement could not be measured.

Lateral load tests at several sites were also performed by applying loads with a hydraulic jack to adjacent concrete test monoliths in which the heads of groups of piles were fixed. Those at Lock 26, Alton, Illinois, are described in Ref. 1).

Pile Driving Practice. Piles were driven almost exclusively with a steam single acting hammer with 5,000-lb. ram and theoretical 36-in. stroke, usually with the aid of a jet except for the last 5 feet of penetration. A record was kept of the indicated bearing capacity for each pile as computed by the Engineering

TABLE I

COMPOSITION OF SELECTED DAMS

Dam No.	Location miles above mouth of Mo. River	Max. head (ft.)	Tainter Gates						Roller Gates					
			Number	Length (Ft.)	Height (Ft.)	Thickness of pier (Ft.)	Size of pier foundation		Number	Length (Ft.)	Height (Ft.)	Thickness of pier (Ft.)	Size of pier foundation	
							Length (Ft.)	Width (Ft.)					Length (Ft.)	Width (Ft.)
26	7.5	25	30	40	30	8	85.	21	3	80	25	15	100	21
25	46.0	15	14	60	25	8	80.5	21	3	100	25	15	101	27
18	215.1	9.8	14	60	20	8	68.5	21	3	100	20	15	95.25	27
9	452.5	9	8	35	15	8	52.0	18	5	80	20	15	94.7	27

TABLE 2

DAM NO. 26

RESULTS OF PILE LOAD TESTS COMPARED WITH PERFORMANCE OF STRUCTURE

Location of test pile	Penetration of test pile	Diameter of test pile		Indicated bearing value, Eng. News formula	Maximum design load per pile		Settlement of test pile for design load construction condition	Maximum test load	Settlement under maximum test load	No. of piles driven in permanent foundation	Average penetration	Average indicated bearing value, Eng. News formula	Period of observation	Total observed vertical settlement (1)	Total observed lateral movement (2)
		Butt	Tip		Operating condition	Construction condition									
	(ft.)	in.	in.	(tons)	(tons)	(tons)	(ft.)	(tons)	(ft.)		(ft.)	(tons)	(yrs.)	(ft.)	(ft.)
Tainter gate Pier No. 3	26	10-3/4	8	37	16.5	23.5	.007	80	.056	.86	37.2	36.1	1937-1947	.052	.04
Tainter gate Pier No. 7	28	12-1/2	8½	34	16.5	23.5	.008	80	.091	186	37.8	34.7	1937-1947	.057	.08
Roller gate Pier No.17	36	13-1/4	10	43	22.0	28.0	.007	70	.032	239	38.9	35.4	1936-1947	.105	.05
Roller gate Pier No. 18	40	12-3/4	9	35	22.0	28.0	.009	80	.034	239	38.3	34.8	1936-1947	.094	.03
Tainter gate Pier No. 30	36	13	9	42	16.5	23.5	.009	60	.069	186	37.6	36.0	1935-1947	.045	.02
Tainter gate Pier No. 33	36	13-1/2	9	42	16.5	23.5	.009	80	.059	186	37.7	39.0	1935-1947	.038	.01

(1) Average of settlement observed on 4 corners of foundation pour for all piers during construction in cofferdam ranged from about .02 to .03 ft. Remainder is the average of that on upstream and downstream ends of piers after removal of cofferdam, except for roller gate piers Nos. 17 and 18 for which remainder is that observed on upstream end of pier only.

(2) Lateral movement is that observed on top of piers at mid-point from 22 Sept. 1937 with no head on dam to 29 Sep. 1947, when head was 22.6 ft. and lateral load on tainter and roller gate pier piles was about 4 tons. If piles beneath the apron adjacent to downstream side of piers were fully affective, lateral load per pile was about 3.25 tons for tainter gate piers and 2.7 tons per pile for roller gate piers.

News formula, x) in order to provide in some measure a correlation between the load tests and the general construction pile driving operations, and as an aid in detecting local foundation variations, though it was known that bearing values thus computed are by no means reliable. 2)

Settlement Observations. Reference points were established on some of the structures to afford an opportunity of correlating results of load and driving tests with actual performance under both vertical and lateral operating loads. Pertinent data are given in Tables 1 to 7 for certain representative locks and dams described below.

LOCK AND DAM NO. 26, ALTON, ILLINOIS

The dam and locks are founded on sand of fine to coarse gradation. In any particular stratum, the sizes of the sand particles are rather uniform with an absence of gradation in sizes conducive to impermeability. The general plan and sections are shown in Figs 2 and 3.

Dam. It will be noted from Table 2 that settlements ranging from 1/2 to 1-1/4 inches and lateral movements from 1/8 to 1 inch have occurred for certain piers of the dam. Records indicate that most of the vertical settlement occurred during and soon after the construction

x) Engineering News Formula: $R = \frac{2Wh}{s+0.1}$

Symbol	Definition	Unit
W	Weight of striking parts of hammer	Pounds
h	Height of fall of hammer	Feet
s	Penetration of pile per blow	Inches
R	Allowable static safe load on pile	Pounds

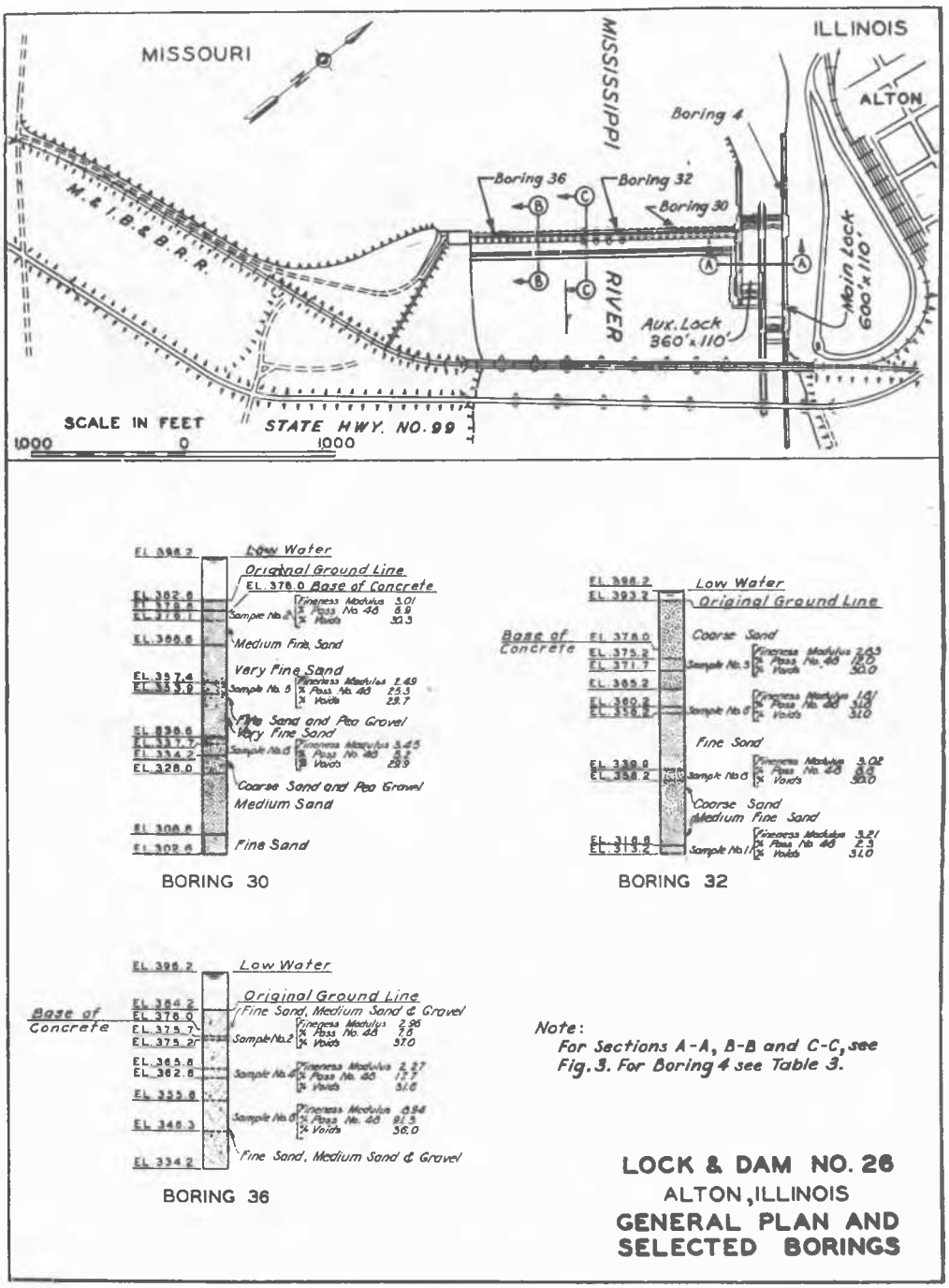


FIG.2

period, and that no significant settlement has occurred in recent years. On the other hand, most of the lateral movement seems to have occurred within the past 4 years, during which there have been a number of floods, and the head has varied from 0.5 to about 25 ft., causing a variation in lateral load per pile of from less than 0.5 to about 4 tons. Since there appears to have been slightly more settlement of the upstream than downstream end of the piers, this apparent lateral movement cannot be explained as rotation about the dam axis.

Lock. Because of the range in river stage, lock walls 51 ft. high are required. Under certain operating conditions loads as great as 40 tons occur on the piles beneath the edges of the walls adjacent to the lock chambers, and as much as 50 tons if either lock chamber is ever unwatered. Accordingly, 3 rows of concrete piles were provided adjacent to the lock side of each wall. Under the monoliths supporting the miter gates all piles are concrete. For the remainder the design load was generally within the allowable limit of 25 tons for timber piles.

For load tests to simulate compaction expected in the permanent foundation, 45 piles were driven, arranged in 5 rows, each with 9 piles. Rows were 3 ft. apart and piles in each row were 3 ft. 6 in. on centers, with concrete and timber test piles in the interior. These tests (Table 3), performed in the wet, indicated that timber piles with 35 ft. and 30 ft. penetration would be adequate for not over about 25 and 20 tons, respectively. These lengths were used for corresponding loads. It was also concluded that either a concrete pile tapering from 18 to 10-3/4 in. or a 16-in. octagonal constant section pile, pointed tip, with 30-ft.

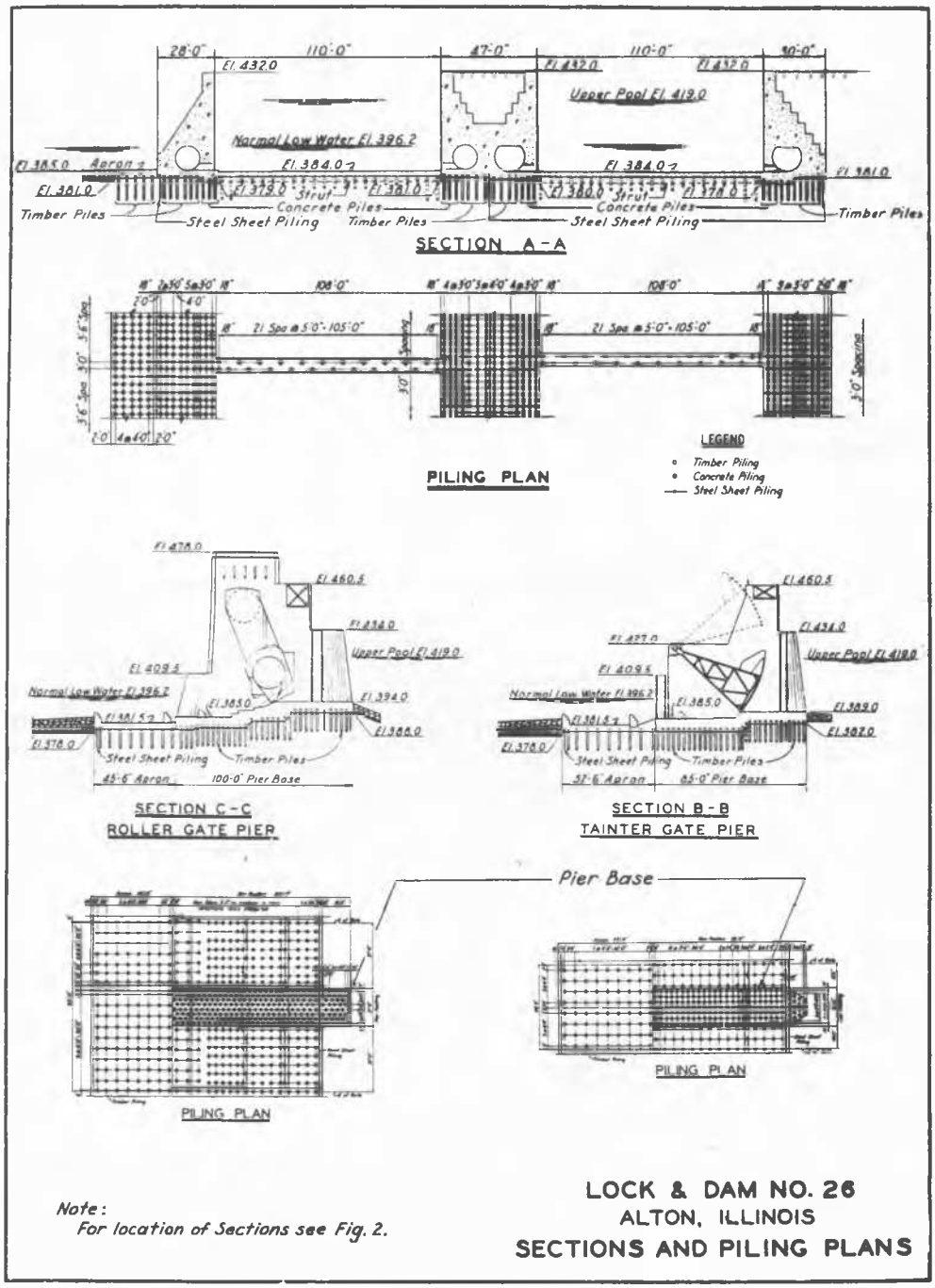


FIG.3

penetration would be adequate for an operating load of 40 tons and a temporary load of 50 tons. The contractor elected to furnish the tapered pile.

From 1940 to 1947 settlement of the intermediate wall ranged from about 0.01 to 0.04 ft., and of the river wall between gates, 0.02 to 0.08 ft. There was no significant settlement of the land wall between gates. Since no points were established on foundation pours, total settlement cannot be determined. That which has occurred is largely in monoliths other than those supporting miter gates.

Alignment checks do not indicate any significant permanent lateral movement of the walls between gates, due no doubt to the system of struts integral with the floor slab between lock walls, and to the supporting apron provided along the river wall as indicated in Fig. 3. The heavy lateral load from 51 feet of backfill which the land wall piles would otherwise carry is thereby distributed also to the piles beneath the intermediate and river walls.

It was recently noted though that reversal of the lateral load on the intermediate wall by alternately filling and discharging the two lock chambers with 20.5-ft. head caused a lateral movement of the top of the wall of as much as 0.05 ft. Since there have been over 33,000 lockages, this is not too surprising.

LOCK AND DAM NO. 25, CAP AU GRIS, MISSOURI

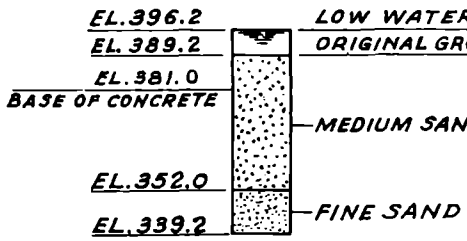
The foundation for both the lock and dam is of sand varying from fine to coarse with occasional pea gravel.

Lock. As at Lock 26, under certain operating conditions unit loads as great as 40 tons

TABLE 3

LOAD TESTS - LOCK No. 26

Type of test pile	Penetration (feet)	Penetration (sq.ft.)	Diameter Butt (in.)	Diameter Tip (in.)	Indicated safe bearing value by Engineering News formula (tons)	Load causing .02 ft. settlement (tons)	Max. test load (tons)	Settlement under max. load (feet)	Settlement remaining after removal of max. test load (feet)	Test time max. load sustained (days)
Timber	25	70	12-1/4	8-1/2	36.9	35	50	.055	.026	7
do.	30	81	12-1/8	8-3/8	45.3	25	50	.087	.073	4
do.	35	100	13-3/8	8-5/8	33.1	30	50	.037	.020	6
do.	40	94	11-1/2	6-1/2	55.4	50	80	.056	.056	3
do.	50	122	12-1/8	6-5/8	74.8	30	50	.085	.038	2.5
Conc. constant section	35	151	16	16	69.6	87.5	100	.031	.014	7.5
do.	30	123	16	16	69.6	90	100	.040	.020	10
Conc. tapered	30	112.9	18	10-3/4	57.0	90	100	.062	.055	9
do.	30	94.0	18	8-1/4	66.1	86	100	.059	.018	12
do.	35	115.8	18	8-1/4	64.2	75.2	100	.060	.049	5



BORING 4

Sieve analyses of samples from boring at location of test piles, land wall.

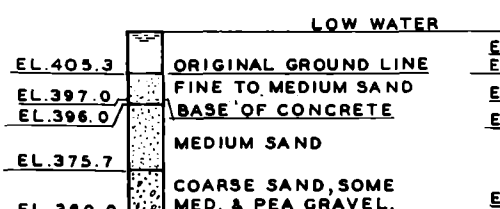
Elevation of Sample	Percentages Passing Screens No. 8	No. 14	No. 28	No. 48	No. 100	Fineness Modulus
389.0	100.0	99.9	67.7	3.4	0.0	2.29
379.0	100.0	100.0	70.3	5.2	0.0	1.35
369.0	100.0	99.9	80.8	21.2	0.0	1.98
359.0	100.0	99.9	90.2	36.6	0.0	1.73
349.0	100.0	99.8	87.6	24.4	0.0	1.88

TABLE 5

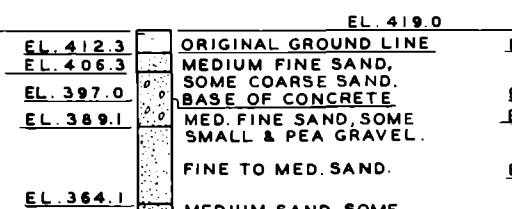
DAM NO. 25

RESULTS OF PILE LOAD TESTS COMPARED WITH PERFORMANCE OF STRUCTURE

Load Test Data									Data on Structure				
Location of test pile	Penetration of test pile (ft.)	Diameter of test pile Butt (in.)	Diameter of test pile Tip (in.)	Indicated bearing value, Eng. News formula (tons)	Maximum design load per pile: Operating condition (tons)	Maximum design load per pile: Construction condition (tons)	Settlement of test pile for design load construction condition (ft.)	Maximum test load (tons)	Settlement under maximum test load (ft.)	Number of piles in permanent foundation	Average penetration (ft.)	Average indicated bearing value, Eng. News formula (tons)	Period of observation (years)	Total observed vertical settlement (ft.)
Tainter gate, Pier 3	31	13	8	18	15.5	22	.005	75	.063	158	31.6	31.7	1937-1947	.05
Tainter gate, Pier 7	32	12¼	8	14	15.5	22	.003	75	.088	158	33.3	38.6	1937-1947	.04
Roller gate, Pier 10	31	12¼	8	23	19.5	20	.009	75	.071	297	31.9	32.6	1938-1947	.04



BORING NEAR PIER 3



BORING AT PIER 7

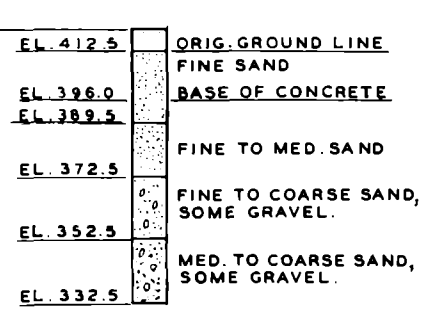
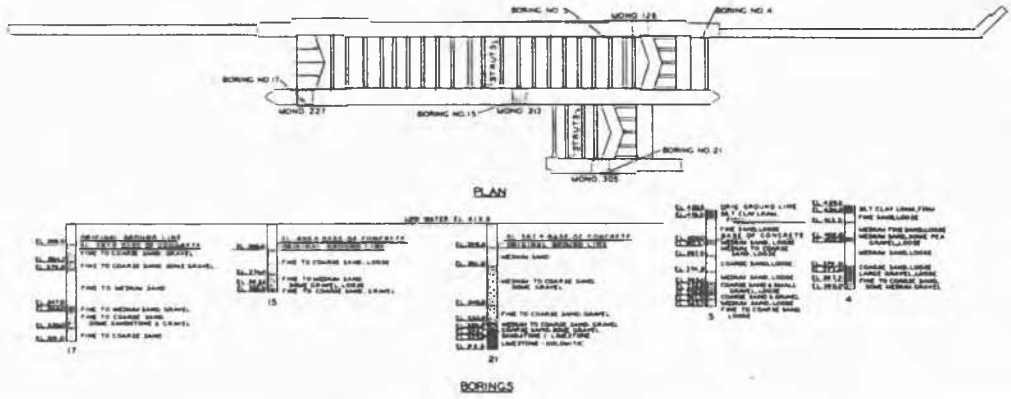


TABLE 4

PILE LOAD TESTS - LOCK NO. 25

Location of test pile	Penetration		Diameter		Indicated bearing value by Engineering News formula	Load causing .02 ft. settlement	Maximum test load	Settlement under maximum load	Settlement remaining after removal of max. test load	Test time maximum load sustained
	(ft.)	(sq.ft.)	Butt (in.)	Tip (in.)	(tons)	(tons)	(tons)	(ft.)	(ft.)	(days)
Land wall Monolith 126	29	115	17-1/4	13	38	60	100	.081	.049	3
Land wall Monolith 126	34	109	14-1/4	10-1/4	40	40	60	.032	.001	5
Intermediate wall Monolith 213	32	117	17	11	52	80	100	.026	.008	6
Intermediate wall Monolith 227	32	89	12-3/8	8-3/4	27	50	60	.092	.066	5
Intermediate wall Monolith 227	31	127	17-1/2	13-3/4	55	60	100	.113	.089	6
River wall Monolith 305	36	97	11-3/4	8-3/4	24	60	120	.076	.047	60 tons, 4 days 120 tons, 1/4 hour



occur on piles adjacent to the lock chambers, and 50 tons if the lock chamber were ever unwatered. To support these loads, after load tests (Table 4) selected large timber piles were used approximating in size and penetration the concrete tapered piles used at Lock 26, with substantial saving in cost.

Virtually all of the settlement in 11 years, 0.01 to 0.04 ft., occurred in the first year after completion. Settlement during construction is unknown. There is no evidence of significant lateral movement as here, too, struts integral with the floor slab distribute the lateral load to the piles beneath both lock walls.

Dam. Readings on the foundations pour of certain piers indicate a settlement during construction of 0.01 to 0.02 ft., with an additional 0.02 to 0.03 ft. since completion (Table 5).

Recors of lateral movements are incomplete. Recent observations, however, do show that reference points on top of certain piers moved downstream from 0.02 to 0.08 ft. from April to November 1947, when the head increased from 0.5 to nearly 14 ft., and the unit horizontal load became about 4 tons.

LOCK AND DAM NO. 18, BURLINGTON, IOWA

The foundations consists of sand interbedded with gravel deposits with occasional thin layers of clay.

Dam. The 151 piles driven in each foundation for tainter gate piers Nos. 2 and 3, between which load tests (table 6) were performed, averaged about 28 ft. of penetration and had an indicated bearing value of about 47 tons, as computed by the Engineering News formula. No data are available as to settlement during construction. Observations for 8 years of operation, however, show a settlement of these 2 piers of only about 0.01 ft. Settlements of other piers range up to about 0.03 ft. Horizontal loads per pile inder normal operating conditions approximate 2.5 tons for tainter gate piers and 3.1 tons for roller gate piers. During the 8 years of operation, alignment observations indicate no significant lateral movement.

Lock. The observed settlement of lock walls 38,5 ft. high, are founded on piles having bout 31-ft. penetration, with normal maximum operating loads of about 24 tons per pile. The foundation is similar to that of the dam.

LOCK AND DAM NO. 9, LYNXVILLE, WISCONSIN

The foundation for this lock and dam also consists of a deep deposit of river sand of medium to fine gradation.

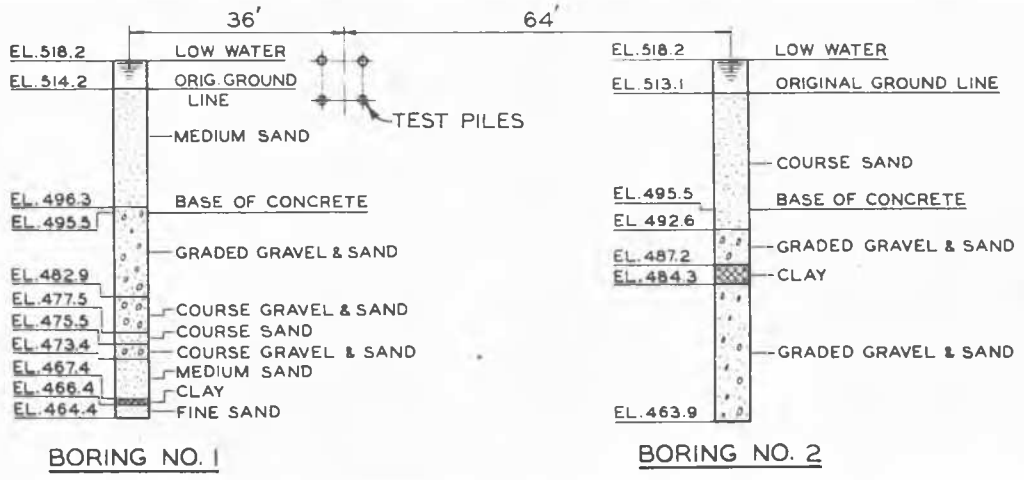
Dam. Observations on points on the foundation pours and later on top of the piers indicate again that of the total settlement ranging up to 0.07 ft., most occurred during and immediately following the construction period. Horizontal loads of about 3.7 tons per pile for

TABLE 6

PILE LOAD TESTS - DAM NO. 18

Location of test pile	Penetration of test pile (ft.)	Diameter of test pile		Indicated bearing value, Eng. News formula (tons)	Maximum design load per pile (tons) (1)	Settlement of test pile for design load (ft.)	Maximum test load (tons)	Settlement under maximum test load (ft.)	Settlement remaining after removal of maximum test load (ft.)
		Butt (in.)	Tip (in.)						
All between Tainter Gate Piers Nos. 2 and 3	27.6	12	8	26	21.0	.006	75	.030	.006
	22.3	12	8	22	21.0	.006	75	.042	.02
	17.4	12-1/2	8	22	21.0	.008	74	.083	.057
	12.2	12	10-1/2	26	21.0	.006	75	.050	.025

(1) Construction condition for tainter gate piers



roller gate and 2 tons for tainter gate pier foundations have not caused significant lateral movement.

Lock. The lock walls, 41.5 ft. high, are supported by piles having ingeneral about 30 to 35 ft. of penetration with normal maximum unit operating loads of about 25 tons. Whereas during the construction period there was an initial settlement of from 0.01 to 0.03 ft., during the past 12 years there has been virtually no additional settlement.

LOCK NO. 2, HASTINGS, MINNESOTA

The foundation for this lock and dam consists in general of a 30-ft. layer of sand overlying two layers of clay, one approximately 60 ft. thick, and a lower one about 10 ft. thick, separated by a layer of sand about 10 ft. thick. Below the lower layer of clay is a compacted sand and gravel or sandstone formation.

The dam and first lock were completed in 1930. The maximum head is 12.2 ft. Both structures are founded on timber piles 30 to 35 ft. long, with a maximum design load of about 30 tons. Due to consolidation of the underlying clay the structures settled about 0.8 ft., though rather uniformly for the river wall and dam. However, the weight of 14 feet of backfill behind the land wall and excavation of the lock chamber has resulted in greater settlement at the heel than toe of the wall, causing the land wall to rotate landward sufficiently to necessitate realignment of the miter gates.

Masonry for a second lock, landward of the first, was completed in 1942. Installation of gates and machinery, deferred by the war, is scheduled for 1948. To eliminate excessive settlement of the monoliths supporting the miter gates, 12-in. by 12-in. steel H piles 132 ft. long with maximum design load of 60 tons were driven completely through the clay into the incompressible stratum below. The remainder of the structure is founded on 25-ft. wood piles with maximum design load of 20 tons. Recent observations indicate about 0.2-ft. settlement for monoliths on wood piles and only about 0.05 ft. for those on H piles. No load tests were performed on the H piles, but the average bearing value per pile indicated by the Engineering News formula was about 68 tons.

Discussion. Consultation with engineering and operating personnel having knowledge of each project indicates that, exclusive of certain approach walls of relatively minor importance, there is no evidence that any of the other upper Mississippi River locks and dams on pile foundations has had greater lateral movement or settlement than those presented herein.

Despite the wide physical separation, there is marked uniformity between the records of driving, the results of load tests, and the performance of those structures founded on piles in sand. From an examination of the tables it will be noted that:

a) With few exceptions the test load required to produce 0.02-ft. settlement in the test pile exceeded the bearing value indicated by the Engineering News formula.

b) In general, the test load on a single pile

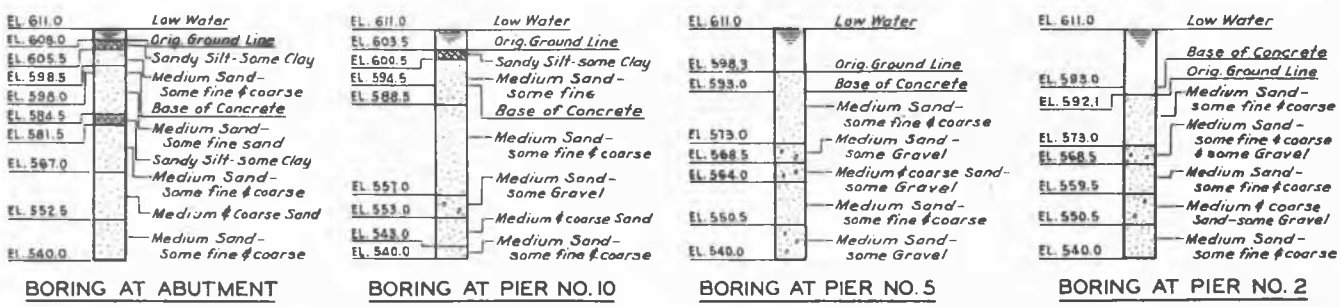
TABLE 7

DAM NO. 9

RESULTS OF PILE LOAD TESTS COMPARED WITH PERFORMANCE OF STRUCTURE

Load Test Data										Data on Structure				
Location of test pile	Penetration of test pile (ft.)	Diameter of test pile Butt (in.)	Diameter of test pile Tip (in.)	Indicated bearing value, Eng. News formula (tons)	Maximum design load per pile: Operating condition (tons)	Maximum design load per pile: Construction condition (tons)	Settlement of test pile for design load construction condition (ft.)	Maximum test load (tons)	Settlement under maximum test load (ft.)	No. of piles driven in permanent foundation	Average penetration (ft.)	Average indicated bearing value, Eng. News formula (tons)	Period of observation (years)	Total observed vertical settlement (ft.)
Roller gate Pier No. 2	35	13½	10	21.5	23	25	.012	60	.088	235	34.1	32	1937-1947	.04
Roller gate Pier No. 5	35	12	9	21.5	23	25	.007	60	.047	235	33.3	33	1937-1947	.07
Tainter gate Pier No. 10	36	14½	8½	15.7	15.5	17.5	.0	60	.096	93	33.5	24	1936-1947	.013
Abutment Monolith C-2	29	13½	9	15.7		25	.015	60	.147	175 (1)	32.3	35	1936-1947	.04

(1) Includes 12 batter piles



required to produce 0.02-ft. settlement also materially exceeded the maximum design load.

c) Nevertheless, in many instances the settlement of the completed structures has exceeded 0.02 ft.

d) The lateral movement of the lock walls has in general been minor.

e) The downstream lateral movement of certain of the piers for the dams having higher heads has exceeded 0.02 ft., probably due to frequent application and release of lateral load with changing river stages and perhaps to some slight adjustment of sand particles surrounding the upper end of the piles because of seepage through the interlocks of the steel sheet piling.

f) Differential settlement or lateral movement has been small.

CONCLUSIONS.

a) Settlement or lateral movement of a structure founded on a large group of piles may be somewhat grater than that indicated by load tests on individual or small groups of piles even in a sand foundation, particularly if there is sustained seepage through the sand around the piles and frequent application and release or reversal of the lateral load.

b) Since no adverse aperational effects have been noted at any of the locks and dams on the upper Mississippi River due to settlement or lateral movement, except in the case of the Old Hastings Lock which was founded on a difficult clay foundation, it is concluded that notwithstanding the relatively small vertical and lateral movements by which the design criterion of 0.02 ft. has in some instances been exceeded, the pile foundations as designed and constructed are satisfactory.

ACKNOWLEDGEMENTS.

The assistance of personnel of the St. Paul, Rock Island, and St. Louis Districts and of the Upper Mississippi Valley Division office of the Corps of Engineers in supplying helpful suggestions and data is gratefully acknowledged.

REFERENCES.

1): "Lateral Pile-Loading Tests", by Lawrence Feagin, Transactions, Am.Soc.C.E., Vol. 102 (1937)

2): "Pile Foundations and Pile Structures," Am.Soc.C.E. Manuals of Engineering Practice, No. 27 (1946)

-o-o-o-o-o-o-o-o-o-