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MAXIMUM SCOUR DEPTHS AROUND A BRIDGE PIER IN SAND AND IN CLAY ARE EQUAL?

by

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SUMMARY

The maximum scour depth around bridge piers in sand is calculated using well established formulas based on experimental model calibrations. There are no such formulas for the maximum scour depth around bridge piers in clay. In practice and by conservatism the maximum scour depth in clay is taken to be equal to the maximum scour depth in sand. However no such evidence exists and common sense tells us that clays scour much more slowly than sand.

This paper presents flume test results of pier scour in clay. The piers are cylinders with diameters varying from 25 mm to 220 mm. The soils were a low plasticity porcelain clay, a medium plasticity armstone clay, a high plasticity bentonite clay and two uniform sands. The results show that the maximum depth of scour is the same in the sands and in the clays. However the rate of scour is drastically different. This shows that in clays a site specific scour rate analysis is necessary while it is not necessary in sands.

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INTRODUCTION

In US practice the maximum scour depth around a bridge pier in sand is calculated by using the "HEC 18" formula (Richardson and Davis, 1995)

$$z_{max} = 2z_o K_1 K_2 K_3 K_4 \left(\frac{D}{z_o}\right)^{0.65} F_o^{0.43} \quad (1)$$

where z_{max} is the maximum scour depth around the bridge pier z_o the depth of flow, K_1, K_2, K_3, K_3 are coefficients to take into account the shape of the pier, the angle between the direction of the flow and the direction of the pier, the stream bed topography, and the armoring effect, D is the pier diameter, and F_o is the froude number defined as $v/(gz_o)^{0.5}$ where v is the mean flow velocity and g the acceleration due to gravity.

For clays there is no such formula and by conservation equation 1 is used for clays. Yet it is well recognized that clays scour much more slowly than sands. In order to investigate if z_{max} is the same in sand and in clay, a series of flume experiments were conducted at Texas A&M University.

THE FLUMES AND THE SOILS

Two flumes were used. The first flume was 457mm wide and the second 1525 mm wide. The diameter of the cylindrical piers varied from 25 mm to 76 mm for the smaller flume and from 76 mm to 229 mm for the larger flume. A false bottom was constructed to allow space for placing the soil and then push the hollow pier in the soil. The water depth in the flumes varied from 0.16 m to 0.4 m and the water velocity from 0.2 m/s to 0.83 m/s.

The soils used were three clays and two sands. The first clay was a low plasticity clay used to make porcelain craftware. The second clay was a medium plasticity clay called armstone also used for pottery. The third clay was a high plasticity clay with a 30% content of bentonite. The first sand was a medium uniform silica sand with a particle diameter D_{50} equal to 0.6mm and 5% passing sieve no. 200 (0.076mm). The second sand was a fine uniform silica sand with a particle diameter equal to 0.14 mm and 0% passing sieve no 200 (0.076 mm). The properties of the soils tested are summarized in Table 1 and the grain size curves are in Figure 1.

THE FLUME TESTS

A total of 43 tests were performed. 6 in the larger flume with porcelain clay and 37 in the smaller flume. Of those 37, 4 were performed with the medium sand, 3 with the fine sand, 2 with the bentonite clay, 4 with the armstone clay, and 24 with the porcelain clay. The clay was prepared in blocks 0.3m x 0.15m x 0.15m in size. The clay blocks were placed side by side, compacted with a metal plate to remove air voids and smoothed out with a hand trowel to obtain a smooth surface. The sand was dumped in a loose state into the soil area around the pier.

The water flow was initiated and measurements were made to record the velocity and the depth of scour. The velocity profile was recorded with an acoustic doppler velocimeter (ADV) and the depth of scour with a point gage mounted on an instrument carriage.

RESULTS OF THE TESTS

The detailed results are described in Gudavalli (1997). The first observation is that the scour hole originated on the front side of the piers at a 45 degree angle and that the scour hole developed on the side and mostly behind the pier with very little scour if any in front of the pier. Therefore, in clays, it may not be wise to place monitoring devices in front of the pier.

The result of a test consists of the scour depth vs. time curve for a given velocity, water depth, pier size and soil type (Figures 2, 3, and 4). As can be seen on Figure 4, even after 200 hours (8.33 days) of flow the scour depth was still increasing. In order to obtain the maximum depth of scour the experimental data was fitted with a hyperbola:

$$z = \frac{t}{\frac{1}{\dot{z}_i} + \frac{t}{z_{max}}} \tag{2}$$

where $\dot{z}_i$ is the initial rate of scour and z_{max} is the maximum depth of scour. In the case of Figure 4 (experiment #41) $\dot{z}_i$ was 1.67mm/hour and z_{max} was 208 mm. Note that the hyperbola fits the data very well. For all the experiments z_{max} was calculated in such a way; the z_{max} values are shown in Table 2.

Figure 5 shows the comparison between a fine sand (experiment #32) and a low plasticity clay (experiment #22) for very similar conditions of pier diameter, water depth and water velocity. For the fine sand z_{max} is 41 mm compared to 48.7 mm for the clay; however the initial rate of scour $\dot{z}_i$ is 840 mm/hr for the sand compared to only 0.95 mm/hr for the clay. This shows that while the maximum depth of scour may be the same for sand and clay the rate of scour in clay may be 1000 times less than in sand.

Figure 6 is a plot of z_{max} vs the pier Reynold's number R_e defined as $R_e = \frac{VD}{\upsilon}$ where υ is the kinematic viscosity of the water $(10^{-6} m^2/s)$. On Figure 6 some of the early experiments where problems occurred are omitted (experiments # 5, 10, and 14). The figure indicates that the maximum depth of scour is the same for clay and for sand and the regression line gives:

$$z_{max}(mm) = 0.18R_e^{0.635} \tag{3}$$

Note that the HEC-18 equation also fits the data quiet well (Table 2).

CONCLUSIONS

The 43 flume tests performed in this study tend to show that the maximum depth of scour in clay occurs behind the pier, not in front of it, and that the maximum depth of scour is the same in sand and in clay. However the rate of scour is drastically different. Therefore in clay it is necessary to have a method which gives the progression of the scour depth as a function of time because, at a very slow scour rate, the maximum depth of scour may not be reached during the design-life of the bridge. Such a method has been developed at Texas A&M University for a given hydrograph.

ACKNOWLEDGEMENTS

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Table 1 - Soil Properties

No.	Property	Porcelain	Armstone	Bentonite	Medium Sand	Fine Sand
1	Liquid Limit, %	34.40	44.20	67.00	-	-
2	Plastic Limit, %	20.25	18.39	27.22	-	-
3	Plasticity Index, %	14.15	25.81	39.78	-	-
4	Specific Gravity	2.61	2.59	2.55	-	-
5	Water Content, %	28.51	26.18	39.28	-	-
6	Mean Diameter D_{50} , mm	0.0062	0.0032	0.0006?	0.60	0.14
7	Sand Content, %	0.00	25.00	0.00	95.00	100.00
8	Silt Content, %	75.00	30.00	35.00	5.00	0
9	Clay Content, %	25.00	45.00	65.00	0	0
10	Shear Strength, kPa (lab. vane)	12.51	16.57	39.56	-	-
11	CEC, (meq/100 g)	8.30	10.00	16.10	-	-
12	SAR	5.00	2.00	21.00	-	-
13	PH	6.00	5.20	8.50	-	-
14	Electrical Conductivity, (mmhos/cm)	1.20	1.10	1.10	-	-
15	Unit Weight, (kN/m^3)	18.0	17.89	17.45	-	-
16	Relative Density				loose	loose

Table 2 - Flume Test Results

Expt No.	Flume Size*	Soil Type**	Z_o (m)	D (mm)	V (m/s)	Re	Fr	Z_o/D	t (hrs)	Z_{max} (mm)	Z_{max} (mm)	
											HYPER	HEC-18
1	S	1	0.4	25	0.47	11750	0.24	16	95	75	98	71.1
2	S	1	0.4	25	0.40	10000	0.20	16	72.3	50	63.5	66.3
3	S	1	0.4	25	0.608	15200	0.31	16	46.9	77	122	79.4
4	S	1	0.4	25	0.317	7925	0.16	16	57.4	40	55	60
5	S	1	0.4	25	0.204	5100	0.1	16	37	8	11	49.6
6	S	1	0.4	25	0.4	10000	0.2	16	92.25	53	65.5	66.3
7	S	1	0.4	25	0.83	20750	0.42	16	16.17	44.8	109	90.8
8	S	1	0.4	75	0.608	45600	0.31	5.33	68.92	104	170	162.2
9	S	1	0.4	75	0.319	23925	0.16	5.33	43.4	58	76.9	122.9
10	S	1	0.4	75	0.204	15300	0.1	5.33	37	22	31.5	101.4
11	S	1	0.4	75	0.4	30000	0.2	5.33	60.25	78	142.8	135.4
12	S	1	0.4	75	0.48	36000	0.24	5.33	63	99	147	146.5
13	S	1	0.4	75	0.39	29250	0.2	5.33	131	95	161.3	134
14	S	1	0.4	75	0.318	23850	0.16	5.33	73	39	49.1	122.7
15	S	1	0.4	75	0.48	36000	0.24	5.33	142.5	116	178.6	146.5
16	S	1	0.4	75	0.83	62250	0.42	5.33	16.17	58	180	185.4
17	S	1	0.16	25	0.266	6650	0.21	6.4	99	27	51.5	46.2
18	S	1	0.16	75	0.266	19950	0.21	2.13	99	44	79.7	94.3
19	S	1	0.16	25	0.348	8700	0.28	6.4	152	53	67.3	54.3
20	S	1	0.16	75	0.348	26100	0.28	2.13	152	74	103	110.9
21	S	1	0.4	25	0.47	11750	0.24	16	54.8	60	-	-
22	S	1	0.4	25	0.315	7875	0.16	16	62.24	26	48.7	59.8
23	S	1	0.4	25	0.41	10250	0.21	16	93.25	48.06	81.8	67.0
24	S	1	0.4	25	0.41	10250	0.21	16	114	48.2	107	67.0

*S = Small Flume (0.46 m wide)
L = Large Flume (1.52 m wide)
**1 = Low Plasticity Porcelain Clay
2 = Medium Plasticity Armstone Clay
3 = High Plasticity Bentonite Clay
4 = Medium Uniform Sand
5 = Fine Uniform Sand

Table 2 - Flume Test Results (Continued)

Expt No.	Flume Size*	Soil Type**	Z_o (m)	D (mm)	V (m/s)	Re	Fr	Z_o/D	t (hrs)	Z_{max} (mm)	Z_{max} (mm)	
											HYPER	HEC-18
25	S	3	0.4	25	0.32	8000	0.16	16	75	55	64.5	60
26	S	3	0.4	25	0.39	9750	0.2	16	37.66	50	59.3	65.5
27	S	4	0.17	50	0.243	12150	0.19	3.4	-	67	-	74.8
28	S	4	0.17	50	0.245	12250	0.19	3.4	-	48	-	75.1
29	S	4	0.32	50	0.348	17400	0.2	6.4	-	85	-	95.1
30	S	4	0.33	50	0.448	22400	0.25	6.6	-	115	-	106.4
31	S	5	0.4	25	0.242	6050	0.12	16	9.23	35	35.8	53.4
32	S	5	0.4	25	0.282	7050	0.14	16	4.87	41	-	57.1
33	S	5	0.4	75	0.212	15900	0.11	5.33	6	70	-	103.1
34	S	1	0.4	25	0.3	7500	0.15	16	114.42	20	28	59.4
35	S	1	0.4	75	0.3	22250	0.15	5.33	114.42	54	106	121.4
36	S	1	0.4	25	0.4	10000	0.2	16	117.4	57	73.5	66.3
37	S	1	0.4	75	0.4	30000	0.2	5.33	117.4	95	133	135.4
38	L	1	0.4	75	0.37	27750	0.19	5.33	154.25	84	156	130.9
39	L	1	0.3	150	0.3	45000	0.17	2	182.5	128	250	202.2
40	L	1	0.25	150	0.39	58500	0.25	1.67	175.5	75	190	176.3
41	L	1	0.3	210	0.316	66360	0.18	1.43	210.66	130	208	230.5
42	L	1	0.3	210	0.404	84850	0.24	1.43	104.33	96	225	255.5
43	L	1	0.3	210	0.317	66570	0.18	1.43	146.67	111	187.5	229.6

*S = Small Flume (0.46 m wide)
L = Large Flume (1.52 m wide)
**1 = Low Plasticity Porcelain Clay
2 = Medium Plasticity Armstone Clay
3 = High Plasticity Bentonite Clay
4 = Medium Uniform Sand
5 = Fine Uniform Sand

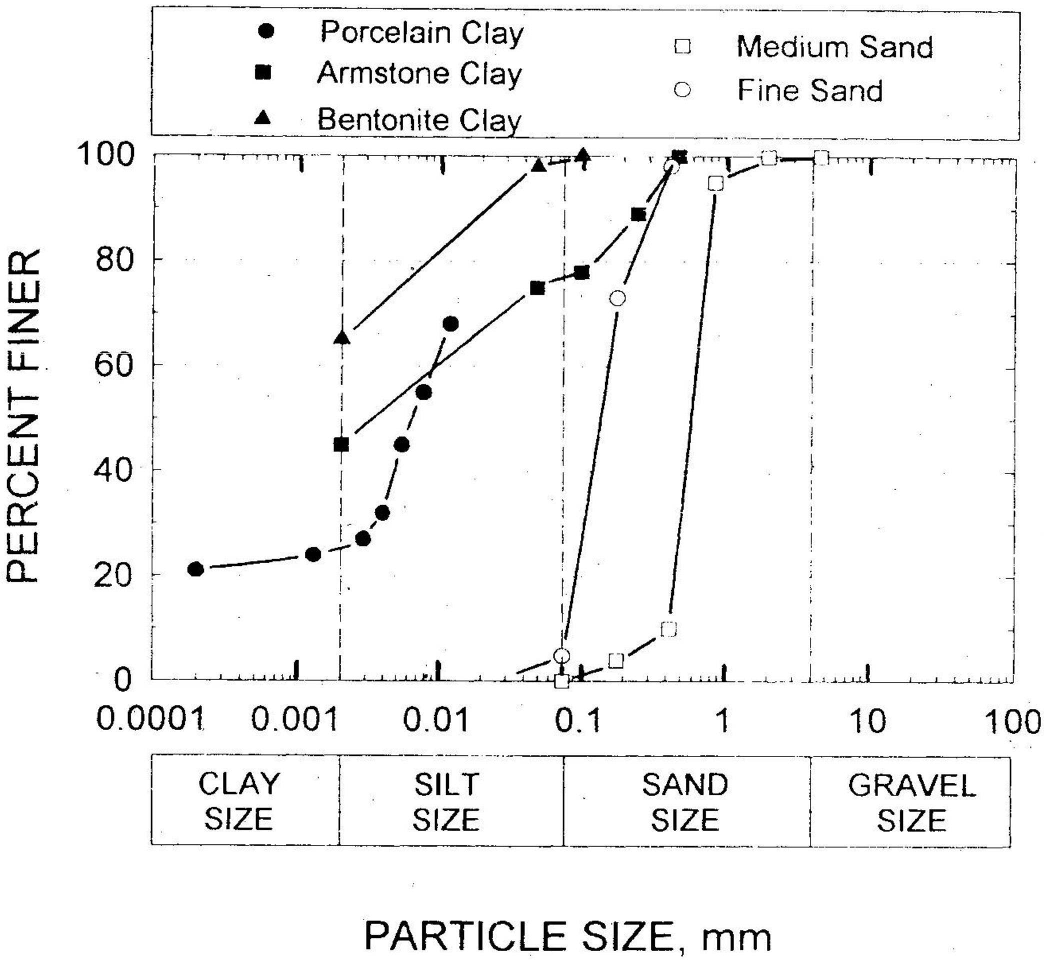

Fig. 1 Particle Size Distributions

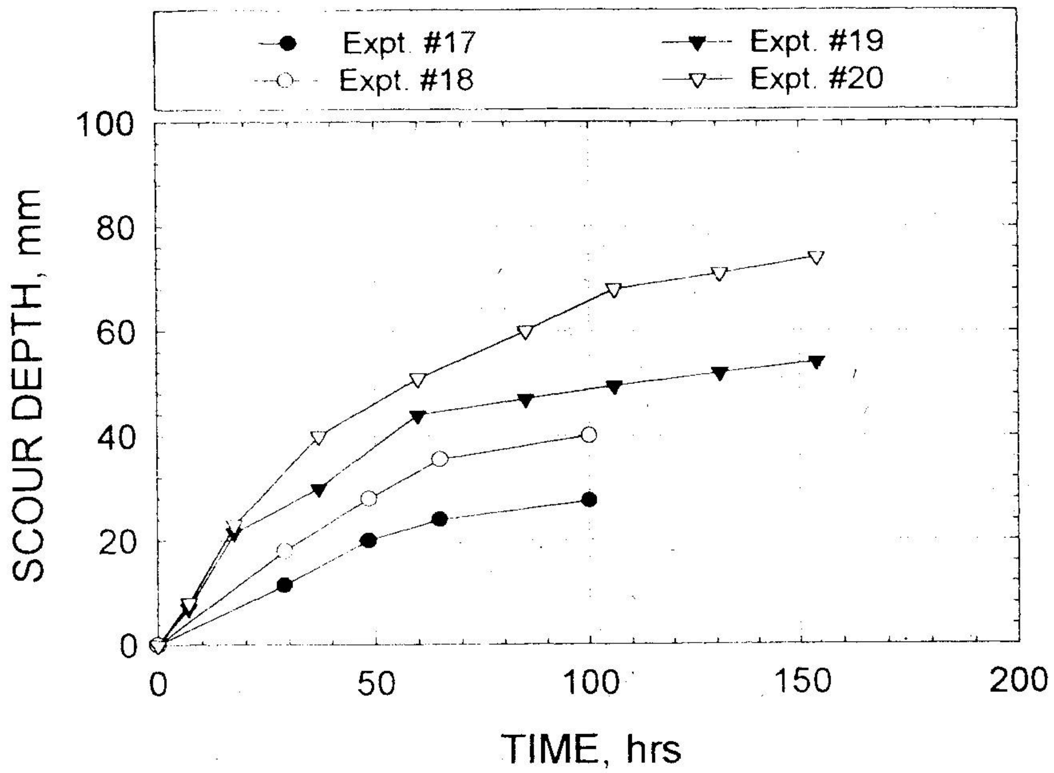

Fig. 2 Scour Depth vs. Time in a Clay

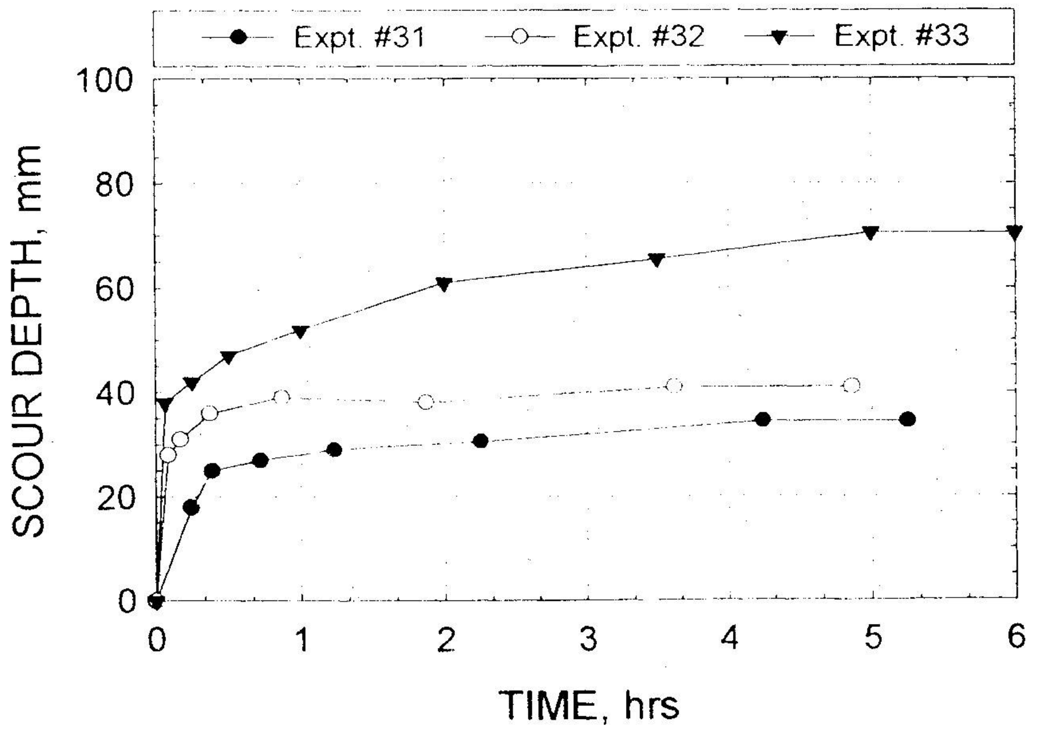

Fig. 3 Sour Depth vs Time in a Sand

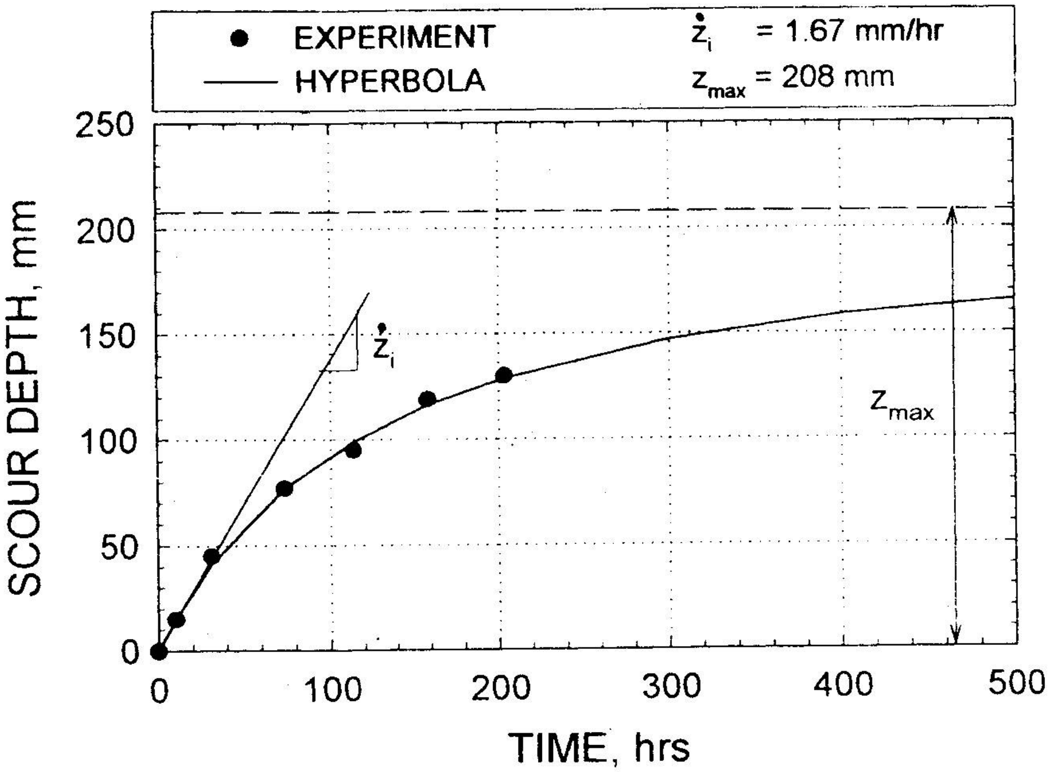

Fig. 4 Hyperbolic Extrapolation for Experiment #41

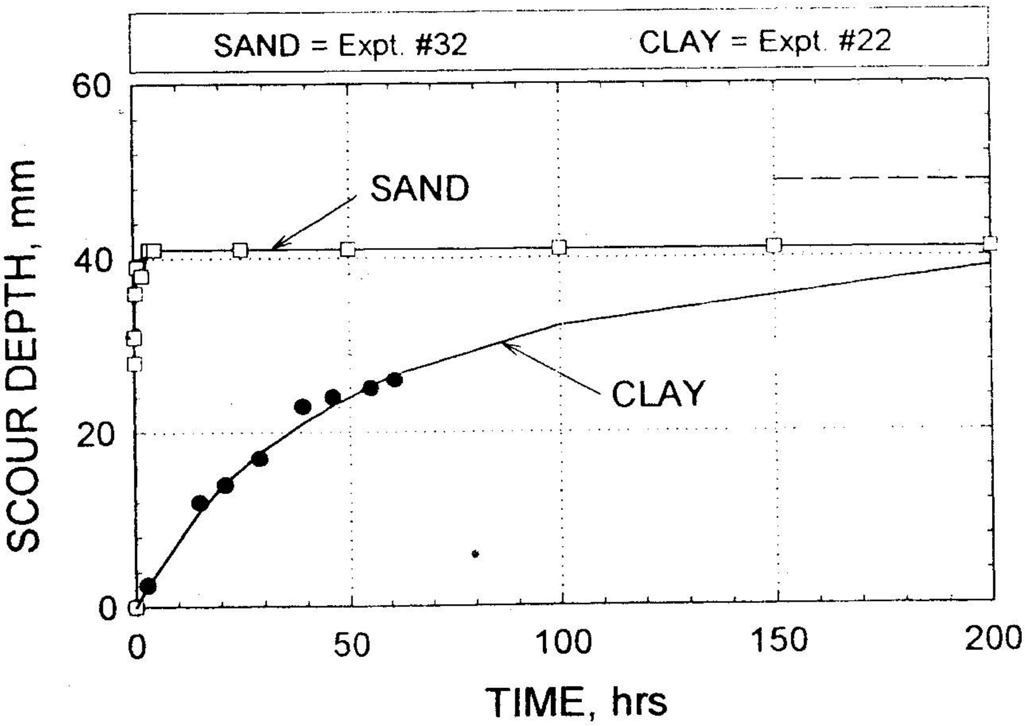

Fig. 5 Comparison Between Exp #32 in Sand and Exp # 22 in Clay

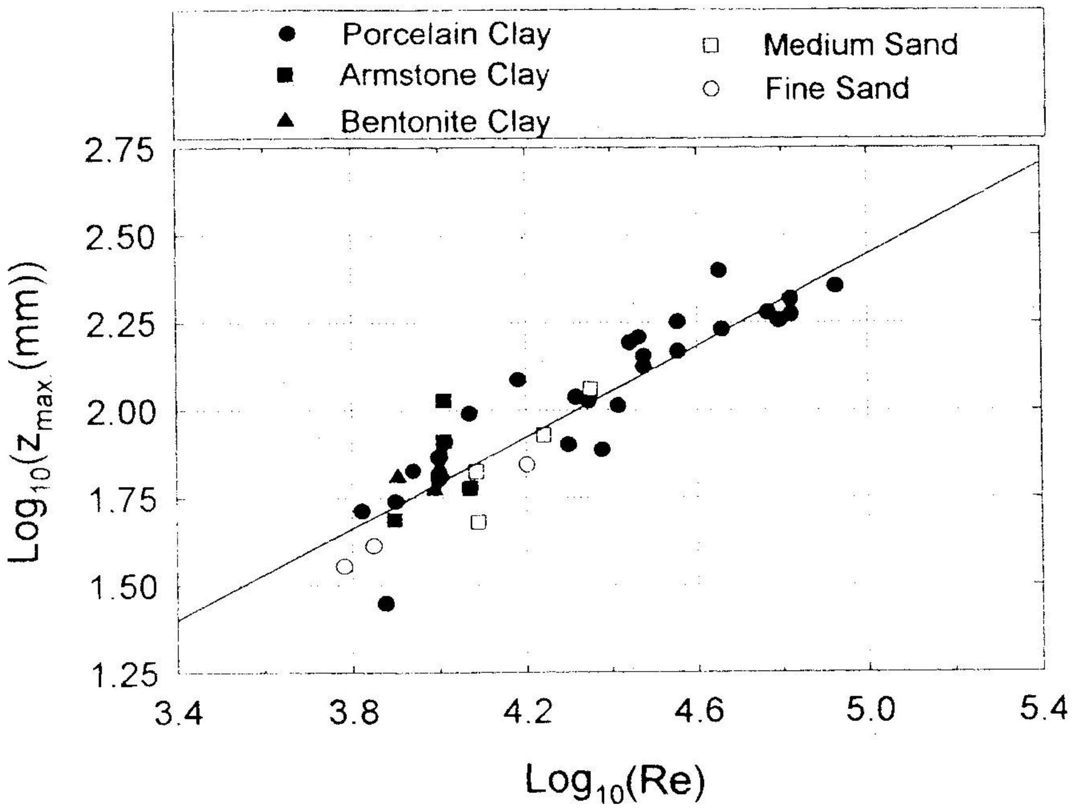

Fig 6 Maximum Scour Depth vs Reynolds Number for two Sands and three Clays

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