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Frictional resistance of drilling fluids as a borehole stabilizers

Amit Kumar Shrivastava*, Deepanshu Jain and Shubham Vishwakarma

*Correspondence: aksrivastava@dce.ac.in
Department of Civil Engineering, Delhi Technological University, Bawana Road, Delhi 110042, India

Abstract

In modern time, due to scarcity of land space in the urban area tall building became essential to cater the housing requirement, which interns causes tremendous increase in the load in the foundation soil for which pile foundation with larger diameter and length becomes more effective solutions in terms of both increased load carrying capacity and settlement reducer. Stabilization of the bore holes with larger diameter and length is a biggest challenge. The stabilization of the excavated borehole can be done using bentonite as well as polymers where the former consists of clay particles which form a low permeable layer around the excavated soil and the later consists of chemicals providing more effective means in the stabilizations. A particular concentration of bentonite and polymer in water is required to achieve the desired property of the fluid so that sides of bore hole can be stabilized, which interns modify the frictional resistance of the pile. In the present study the concentration of bentonite and polymer is varied in water to achieve optimum concentration so that desired property to stabilize the bore is achieved. A series of direct shear test is performed by spreading the bentonite and polymer slurry on shearing plane to study the effect of these fluids on frictional resistance of the pile. The test results reflect that the effect of both the slurry is to reduce the frictional resistance of the pile but reduction is more in case of bentonite than polymer. Based on the experimental results pull-out strength of a pile of given diameter and length is calculated by method suggested by the IS code for both slurry and the result is compared with result of pull out test performed on physically modelled pile on the fabricated experimental setup. The two results are compared and it is observed that IS code method under predict the pull out strength and hence a modification factor is proposed.

Keywords: Drilling fluid, Pile, Frictional resistance, Bentonite, Polymer

Background

Introduce the problem

Since last 70 years, to carry the load of the structures namely three types of foundation system were used such as raft foundations, pile and piled raft foundations where former has limited to the rise building and later have used in high rise building. For pile and piled raft foundations, different drilling fluids are used to stabilize bore hole such as bentonite and polymer. Mineral slurries are the commonly used drilling fluids, for the stabilization of the borehole in various constructions such as pile foundation, diaphragm wall panels etc. Bentonite being economical has been the most commonly used mineral slurry. Bentonite regains its strength due to remolding, when allowed to hydrate in water as it shows a thixotropic behavior with time thus bentonite particles form an impermeable layer of filter cake around the exposed soil layer which helps in borehole stabilization. The ultimate bearing capacity of a pile foundation is the sum of end bearing resistance as well as frictional resistance around its shaft, but various researchers have shown that the frictional resistance offered by the pile is found to be reduced due to the formation of a soft layer with the use of bentonite as a borehole stabilizer which is required to be formed to keep the soil intact in the borehole, thus indulges in compromising with the reduction in the overall ultimate load carrying capacity of the pile. Another problem associated with the bentonite, it is geo-hazards and leads to disposal problems. This led to the development of material, such as polymer fluids which helps in stabilizing the borehole without significantly affecting the frictional resistance of the pile. To stabilize the bore hole it was found that higher percentage of bentonite is required to achieve desired properties of fluid as compared to polymer as the required parameters suggested by the IS code for bentonite fluid. One of the traditional reasons behind switching from bentonite to polymer is its operational benefit. There are certain sites where it becomes difficult to construct a separate bentonite plant due to space restrictions thereby leading to the use of polymer as drilling fluid.

Numerous works has been done by various researchers in establishing better understanding in this regards. Majano et al. [6] observed higher angle of wall friction when polymer was used as a drilling fluid as compared to bentonite slurries. Ata and Neill [1] through microscopic examination of polymer found that polymers are suitable for most of the soil has squeezes into the pores and attains any shape helping in stabilization of soil, they also mention the process of coiling in which polymers break down due to calcium ions presents in the concrete. Brown [5] quoted that polymer promotes an excellent bond between concrete and soil but Frizzi et al. [7] observed high end bearing resistance of pile when bentonite slurries were used in contrast to polymer slurries. In a similar process Lam et al. [2] through a field trial on three piles in east Landon observed polymer outperformed their counterpart bentonite slurry as the former produce higher load capacity. In recent time, environment protection has evolved to be one of the major concerns for the world. Thus several restrictions have been imposed on the final disposal of liquid waste. Lam and Jefferis [3] have mentioned that since polymer is used in very small concentration as compared to bentonite, can be broken down easily with oxidizing agents such as hypochlorite (bleach) so that after the colloidal particles settles the supernatant liquid be disposed to sewer and they also mentioned the operational benefits of polymer fluids over bentonite fluid and has mentioned such a site in Glasgow as polymer fluids neither require multiple holding tanks for slurry hydration nor separations to recover the used fluid. Lam et al. [4] explained the phenomenon of soft toes, reducing load carrying capacity of foundation due deposition of soil particles on the bottom of polymer fluid and quoted the necessity of removal of soil particles using suitable construction technique.

This paper thus presents the results of a laboratory investigation carried to determine the effect of supporting fluids (polymer and bentonite) on the frictional resistance between sand and modeled concrete pile, which includes experimental pull out test in a fabricated steel tank and comparison of theoretical as well as experimental results.

Characterization of materials

Polymer and bentonite

The polymer used for the experimental work was available in dry crystalline form composed of polyacrylamide with associate functional groups which forms long chain hydrocarbons when mixed in water and increases its viscosity. The engineering properties of bentonite and polymer slurries include viscosity and density was determined in laboratory. Sand content and pH are also determined. Measurement of these characteristics is done in the determination of the slurry's ability to build up a filter cake. These properties are influenced by the amount of bentonite and polymer present, the method and duration of mixing, time without agitation, and the amount of impurities present. The bentonite from Kutch region of Gujrat, India was used for the experimental work and had the following specifications: liquid limit, plastic limit, shrinkage limit, and sand content are equal to 498, 54.36, 12 and 0.53 % respectively.

Soil properties

The excavated soil from Noida region of Uttar Pradesh, India was used for the experimental work and had following properties:

- Specific gravity: $G_s = 2.67$
- Gradation of soil: $C_u = 1.56$; $C_c = 1.19$; soil classified as poorly graded sand (SP) as per [8]
- Optimum moisture content: 11.8 %
- Angle of internal friction: $\phi = 41.28^o$

Experimental program

The different concentrations of polymer and bentonite, available in the crystalline and powder form respectively, were added in water and the desired property is measured as per the standard practice. The desired property of bentonite is density = 1.05 g/cc, Marsh Cone viscosity more than 40 s, pH value between 9.5 and 12, silt content <1 % and the liquid limit should not be less than 400 %. But for the polymer there are no guidelines suggested but it is important of stabilization bore to have the marsh cone viscosity more than 40 s and pH value between 9.5 and 12. The total work is divided into three parts: characterization of drilling fluid, determination of different properties of drilling fluid by varying the concentration and time, determination of frictional resistance of drilling fluid, theoretical determination of uplift capacity of the pile using the experimental results of frictional resistance for different boring fluid, fabrication of experimental setup to determine uplift capacity of physically modelled pile bored in a hole stabilized with different boring fluid and finally the theoretical and experimental work is compared.

Rheological properties of drilling fluids

The viscosity of the solutions has been measured as marsh-funnel viscosity of the samples and the pH value of the solutions were noted using the electronic pH meter device, after neutralizing it in a buffer solution of pH value 7. The density of the fluid solutions was measured using a calibrated hydrometer.

Effect of concentration

As polymer was available in dry state, an optimum dosage was required to be known in order to form the drilling fluid. Polymer and bentonite were added in different concentrations to compare its effect on the viscosity, density and pH of the water. In order to investigate the effect of polymer concentration, different concentrations of polymer ranging from 0.002 to 0.5 % were added in a liter of water. Bentonite concentration was kept in range of 0–9 % and to obtain lump free solutions as well as for proper mixing a mechanical device called jar apparatus, in which solutions were mixed for 30 min at 250 rpm. The properties of the solution were determined after 2 h of the sample preparation. Studying from the literature review, since there is no upper limit to the viscosity of polymer fluid, two suitable concentrations i.e. a low concentration value (0.006 %) and a high concentration (0.1 %) value of polymer were selected to check the effect of other parameters. The bentonite concentration of 4 % satisfy the criteria of drilling fluid to stabilize the bore hole, hence this % is selected for other tests.

The effect of increase in the concentration of the bentonite on rheological properties of fluid is presented in Table 1. It was observed that the effect of addition of bentonite in water is to increase the density, viscosity and pH value, but the effect of increase in concentration of bentonite in water is to increase both viscosity and density but there is no effect on pH value.

The effect of polymer concentration on rheological properties of fluid is presented in Table 2. The experimental results indicate that there is no effect of concentration of polymer on the density of fluid it is all most constant at unity which is of water. The increase in the concentration of polymer cause increase in the viscosity, but pH value increases with the addition of polymer but pH value remains constant with the increase in the dose of the polymer. The increase in viscosity is due to presence of functional groups in the polymer which has the ability to form long chains of hydrocarbons.

It can be seen a very small % of polymer is required as compared to bentonite to get desired viscosity. About 4 % of bentonite is required to have the viscosity of 46.88 s but the polymer dose of 0.002 % can produce a viscosity of 44.29 s. It means the quantity required for the polymer is about 2000 times less than that of bentonite and the cost of polymer is about 200 times of that polymer, so it will be cost effective. Bentonite is hazard to environment also and disposal of bentonite is a challenge and will cause land and water pollution. Use of polymer will also reduce the whole cycle of piling operations because it does not require flushing of the bore as it is done if bentonite is used. Because bentonite slurry is heavy and settle at the bottom of bore.

Table 1 Rheological properties of bentonite fluid

Bentonite concentration (%)	Viscosity of fluid (s)	Density of fluid (g/cm^3)	pH
0	36.40	1.000	7.1
2	40.00	1.005	9.2
4	46.88	1.050	9.3
5	57.51	1.100	9.3
6	72.31	1.200	9.3
9	122.00	–	9.3

Table 2 Rheological properties of polymer fluid

Polymer concentration (%)	Viscosity of fluid (s)	Density of fluid (g/cm^3)	pH
0	36.43	1	7.7
0.002	44.29	1	8.1
0.004	50.00	1	8.3
0.006	60.00	1	8.4
0.008	67.09	1	8.4
0.01	71.00	1	8.4
0.02	78.37	1	8.4
0.03	82.00	1	8.4
0.04	85.89	1	8.4
0.05	100.03	1	8.4
0.1	133.0	1	8.4
0.5	340.88	1	8.4

The pH value of both polymer and bentonite slurry is less than the desired, hence it can be increased to desired level by addition of sodium hydro oxide. The pH of the slurry is kept in a range, so as to avoid any adverse effects on the pile reinforcement, casing, or concrete.

In order to increase the pH value of solution, sodium hydroxide NaOH was added at different concentrations of (0.01, 0.1, 0.5, and 1 %). In these investigation first bentonite fluids of 4 % and polymer fluids of two selected concentrations i.e. 0.006 and 0.1 % were formed after mixing them for 30 min at 250 rpm and the rheological properties were determined just after the mixing of these solutions. The pH value of the prepared solutions was varied by adding NaOH in different % and the solutions were mixed again at the rate of 250 rpm for 30 min. The change in viscosity and density of suspension was determines just after mixing of the solutions and the results are presented in Tables 3 and 4 for bentonite and polymer respectively. The experimental results, shows the effect of increase in % of NaOH is to increase the pH value of the suspension, but the Marsh viscosity and density of bentonite drilling fluid increases as the pH changes from 9.3 to 9.6 and thereafter it decreases. Similar effect was also observed in case of polymer fluid, which has shown an increment in Marsh viscosity of fluid up to a certain pH value and thereafter it started decreasing, for both the lower as well as higher concentration of polymer and the optimum dose of NaOH in the case of bentonite and polymer is 0.1 and 0.05 % respectively.

Table 3 Effect of increase of pH on bentonite fluid properties

4 % concentration bentonite slurry			
NaOH (%)	**pH**	**Viscosity (s)**	**Density (g/cm^3)**
0	9.3	45.54	1.025
0.01	9.4	50.21	1.03
0.1	9.6	63.10	1.04
0.5	10.1	61.41	1.05
1	10.6	60.52	1.05

Table 4 Effect of increase of pH on polymer fluid properties

Sodium hydroxide NaOH (%)	Polymer concentration 0.006 %		Polymer concentration 0.1 %	
	pH	Viscosity (s)	pH	Viscosity (s)
0	8.3	60.39	8.4	123.46
0.01	8.8	64.24	8.9	157.19
0.05	9.9	69	9.7	160.38
0.1	10.6	68.01	10.2	153.38
0.5	12.1	64.61	11.9	152

Effect of time

Mineral slurries are thixotropic in nature and usually gain their strength with the passage of time, thus it required to be stored before brought to use, but this effect is not well known for the polymer fluids. Hence, it is important to find out the performance of polymer with the time during the process of excavation till the time of concreting, polymer fluid must retain its properties for its efficient working as a borehole stabilizer, making essential to study this effect.

In this investigation bentonite and polymer were added separately in 1.5 l of water and the solution were mixed for 30 min at 250 rpm in the jar apparatus. The Marsh viscosity, pH and density of the prepared solutions were then measured at different time intervals after mixing of bentonite and polymer. The effect of time on the Marsh funnel viscosity of 4 % concentration of bentonite slurry is presented in Table 5, the results reflect that the viscosity of fluid increases as the time passage, because bentonite particles have tendency to get swell and gain strength with time due to its thixotropic nature. Similar effect was also observed on the density of fluid which has also increased with the passage of time.

But in case of polymer fluid density of the fluid remained constant with time and was equal to unity. The effects of time on the Marsh viscosity at low and high concentration of polymers are presented in Table 6. It can be observed that for low concentration fluid, the viscosity increases for the first 2 h of mixing and thereafter it decreases with time whereas for high concentration fluid there was a decreasing trend from the time of mixing. The decrease in active concentration of polymers may be one of the probable reasons for this trend.

Table 5 Effect of passage of time on bentonite fluid properties

4 % concentration bentonite slurry			
Time after mixing (h)	pH	Viscosity (s)	Density (g/cm^3)
0	9.3	45.20	1.025
0.5	9.3	45.60	1.025
1	9.3	46.32	1.03
2	9.3	47.54	1.03
5	9.3	48.69	1.04
24	9.2	51.5	1.07
48	9.1	52.32	1.10

Table 6 Effect of passage of time on polymer fluid properties

Time (h)	0.006 % polymer concentration		0.1 % polymer concentration	
	pH	Viscosity (s)	pH	Viscosity (s)
0	8.3	61	8.4	133
0.5	8.3	61	8.4	133
1	8.4	61.1	8.4	130.23
2	8.4	62.23	8.5	128.1
5	8.4	60	8.6	125
24	8.4	56.29	8.6	118.22
48	8.4	52	8.6	114.09

Effect of addition of silt in the drilling fluid

When excavation proceeds, there is a possibility that loose soil particles of soil may fall in the drilling fluid. The presence of silt or sand may affect the density of the fluid affecting the working condition. When concrete is poured using tremie, it is required to have low density drilling fluid, which should rise due to its light weight. Moreover silt if present in the suspension, may collect on the reinforcement; this may hinder the proper bonding between concrete and reinforcement. To investigate this known % of silt is added to two different concentrations of bentonite and polymer. The effect of silt content on rheological properties of bentonite fluid is presented in Tables 7 and 8, and results indicate that both density and viscosity increases with the addition of silt and pH value decreases with the presence of silt content for both the % of bentonite concentration tested, it indicate that proper flushing is important so that silt can be removed from the bore before concreting start. It is difficult to find Marsh funnel viscosity because with the addition of silt flock is formed which clogged the funnel.

The effect of silt content when polymer is added to water is investigated and the results are tabulated in Tables 9 and 10. It can be observed that that there is no effect of silt content on density of fluids and it remains constant at 1. It can be observed that the pH

Table 7 Effect of silt content on 4 % bentonite concentration of fluid

Time after mixing (h)	Silt content added (%)	4 % concentration of bentonite			Silt content added (%)	4 % concentration of bentonite		
		pH	Viscosity (s)	Density (g/cm^3)		pH	Viscosity (s)	Density (g/cm^3)
0	0	9.3	45.41	1.025	5	9.0	53.15	1.06
2	0	9.3	47.10	1.03	5	9.0	54.67	1.10

Table 8 Effect of silt content on 6 % bentonite concentration of fluid

Time after mixing (h)	Silt content added (%)	6 % concentration of bentonite			Silt content added (%)	6 % concentration of bentonite		
		pH	Viscosity (s)	Density (g/cm^3)		pH	Viscosity (s)	Density (g/cm^3)
0	0	9.3	71.23	1.2	5	9.0	–	1.21
2	0	9.3	73.10	1.2	5	9.0	–	1.23

Table 9 Effect of silt content on properties of low concentration polymer fluid

Time after mixing (h)	Silt content added (%)	0.006 % concentration of polymer			Silt content added (%)	0.006 % concentration of polymer		
		pH	Viscosity (s)	Density (g/cm^3)		pH	Viscosity (s)	Density (g/cm^3)
0	0	8.3	59.23	1	5	8.1	64.23	1
2	0	8.3	60	1	5	8.1	48.27	1

Table 10 Effect of silt content on properties of high concentration polymer fluid

Time after mixing (h)	Silt content added (%)	0.1 % concentration of polymer			Silt content added (%)	0.1 % concentration of polymer		
		pH	Viscosity (s)	Density (g/cm^3)		pH	Viscosity (s)	Density (g/cm^3)
0	0	8.4	134.09	1	5	8.1	144	1
2	0	8.5	132.06	1	5	8.1	123.28	1

of the solutions decreased on addition of silt content in both low as well as high concentrations polymer fluids whereas the effect remain unchanged with time. The marsh viscosity of the fluid, just after mixing, increased due to presence of silt particles (in suspension) but after 2 h the viscosity of the top fluid was decreased, as the silt particles got settled. It suggests that during excavation loose soil particles such as silt and sand may settle down due to low density of the fluid and can be removed with suitable construction technique otherwise will form a soft toe and may lead to reduction in the load carrying capacity of foundation.

Interface friction resistance of soil-drilling fluid

The effect of drilling fluid on the frictional resistance of soil was determined by performing direct shear test. As the direct shear test assumes a fixed pre-failure plane, the frictional resistance of soil was obtained when a layer of drilling fluid was placed on that plane and sample is sheared. The dry soil was mixed with optimum moisture content and compacted in the lower half of the direct shear mould. Thereafter, the drilling fluid (10 ml) was poured on the top of it and kept undisturbed for 30 min as shown in Fig. 1. The soil was again compacted to fill the upper half of the mould to obtain a fixed unit weight of $15.8 kN/m^3$. The mould was sheared at different normal loadings for each concentration to obtain the shear parameters of the specimen.

Theoretical uplift capacity of pile

The uplift capacity of the pile foundation (Q) as per Indian Standard: IS 2911 [9], is the sum of skin friction resistance of soil and self-weight of pile (W_p) as given in Eq. 1.

$$\boldsymbol{Q} = \sum \boldsymbol{K P_D} \tan \delta \boldsymbol{A_s} + \boldsymbol{W_p} \tag{1}$$

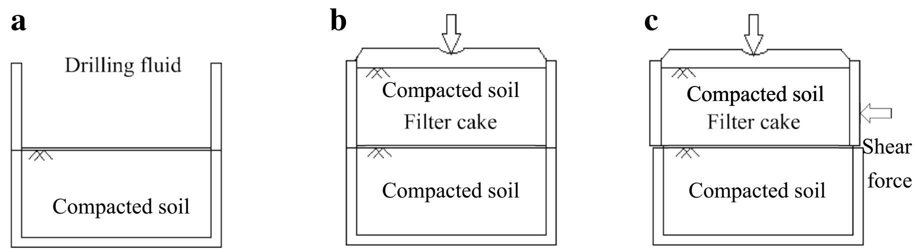

Fig. 1 Sketch diagrams showing arrangement of the interface direct shear mould during: **a** soil placement and application and filtration of slurry; **b** placement of soil in upper half of the mould; **c** shear force application

where, P_D = effective overburden pressure at pile tip, A_s = surface area of pile shaft, δ = soil − pile friction angle obtained by taking δ equal to ϕ values, K = coefficient of earth pressure.

K depends on the nature of soil strata, type of pile and the method of construction. For driven piles in loose to dense sand with ϕ between 30° and 40°, K values is varying from 1 to 1.5.

Frictional resistance of model pile

The purpose of the investigation was to determine the effect of bentonite and polymer fluid, used as borehole stabilizer, on the frictional resistance of soil-concrete interface. Pull out test were performed in fabricated experimental setup in the premises of Delhi Technological University, Delhi. To determine the uplift capacity of five bored cast in situ concrete model piles (length and diameter of pile were 0.35 and 0.045 m respectively), with one of the piles casted without any drilling fluid and two with bentonite drilling fluid (4 and 6 % bentonite concentration) and the rest with polymer drilling fluid of 0.006 and 0.1 % polymer concentration, a suitable steel tank of size $1.5 \times 0.9 \times 0.6\ m^3$ was selected. The tank dimensions were enough to ensure no effect of sides of steel tank on the zone of reactions transferred by the pile during uplifting (more 8 times the diameter of pile). The maximum theoretical uplift capacity for model pile computed from theoretical analysis was multiplied with a factor of safety, 3, to determine the required breaking strength of string. A suitable wire rope of 3 mm diameter was then selected and the corresponding root diameter of the pulley required was 0.036 m (4 cm root diameter pulley was used). The two pulleys were clamped on the hooks of a steel girder just above the steel tank to perform the pull out test.

A concrete mix with added silica flumes was prepared, possessing enough workability and 7 days strength of 18.1 MPa, to be used for casting of piles. After 7 days of casting the test was performed to obtain the uplift capacity of the pile. Figure 2 shows the sketch diagram of the experimental setup.

Results and dicussion

Shear parameters of soil

The results obtained from the direct shear test conducted to determine the effect of frictional resistance of soil with different drilling fluid concentration is as follows:

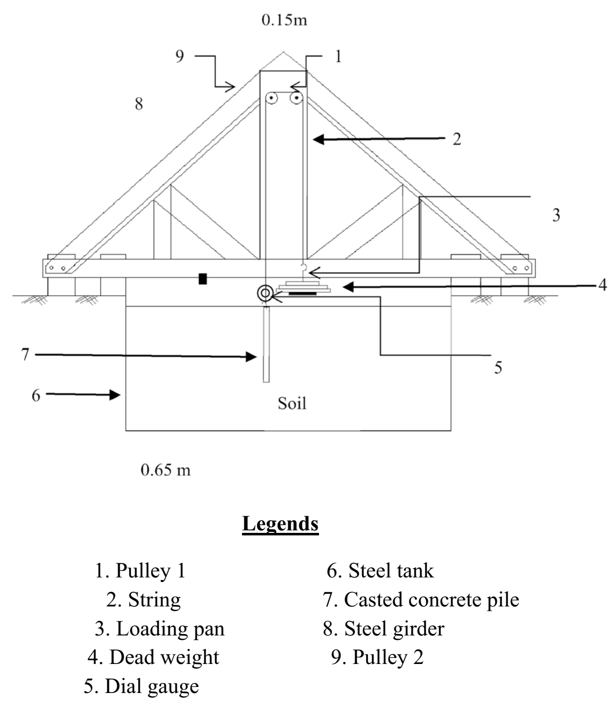

Fig. 2 Experimental setup. *1* Pulley 1, *2* string, *3* loading pan, *4* dead weight, 5 dial gauge, *6* steel tank, *7* casted concrete pile, *8* steel girder, *9* pulley 2

Bentonite fluid

As the concentration of bentonite was increased in the drilling fluid, the angle of internal friction of soil was found to be decreased. This decrease was due to the formation of a soft layer of bentonite which causes reduction in the shear strength of soil. As the concentration increases, the Marsh viscosity of the fluid increased thus the thickness of layer also increased causing reduction in the frictional resistance as given in Table 11.

Polymer fluid

The test results with different polymer concentrations used as drilling fluid is presented in Table 12, although with the increase in polymer concentration Marsh viscosity of the fluid increased at a higher rate, as compared to their counterpart bentonite slurries, but the reduction in the shear strength of soil was very less. Results shows that the angle of

Table 11 Result data for Marsh funnel viscosity and direct shear test for bentonite slurry

Bentonite concentration (%)	Marsh viscosity (s)	ϕ°
0	36.43	41.28
2	40.00	40.17
4	46.88	37.38
6	72.31	32.68
9	122.00	26.44

internal friction of soil reduces for polymer as well as bentonite case but the reduction was more significant for the later.

Theoretical analysis

Theoretically for the determination of uplift capacity of the pile, the angle of internal friction of soil computed from the direct shear test results are used for the concrete-soil interface friction angle. Thus assuming that when a layer of drilling fluid is formed between concrete and soil, the change in the angle of internal friction is same as obtained from the direct shear test results the angle of internal friction obtained from the above experiments, the ϕ values were used for calculating the theoretical uplift capacities of model and prototype pile (scale of 1:15).

The theoretical uplift capacity for model pile ($l = 0.35$ m and $d = 0.045$ m) and prototype pile ($L = 5.25$ m and $D = 0.675$ m) for different cases using Indian Standard method have been tabulated in Table 13.

The load versus displacement response of the model pile obtained from the pull-out test for different drilling fluids has been shown in Fig. 3. The concrete pile casted without using any drilling fluid had higher uplift capacity as compared to other cases where drilling fluid was used. Use of drilling fluid reduced the uplift capacity of pile but the reduction was more significant for piles with bentonite, it may be due to effect of soft filter cake formation on the side of the excavated borehole. From the experiment it was observed that in all the cases with or without use of drilling fluid, failure occurs within 2.5–3.5 mm displacement. The frictional resistance of soil was calculated by deducting the self-weight of the pile from the obtained uplift capacities and presented in Table 14.

Table 12 Result data for Marsh funnel viscosity and direct shear test for polymer slurry

Polymer concentration (%)	Marsh viscosity (s)	ϕ°
0	36.43	41.28
0.006	60.00	40.1
0.01	71.02	39.31
0.05	100.09	38.07
0.1	133	37.07

Table 13 Theoretical uplift capacity of model pile and corresponding prototype pile

Drilling fluid	ϕ°	Uplift capacity (kN)	
		Model (Q_{mt})	Prototype (Q_{pt})
No drilling fluid	41.28	0.194	654.96
0.006 % polymer	40.1	0.187	630.14
4 % bentonite	37.38	0.171	575.87
0.1 % polymer	37.07	0.169	569.97
6 % bentonite	32.68	0.145	490.78

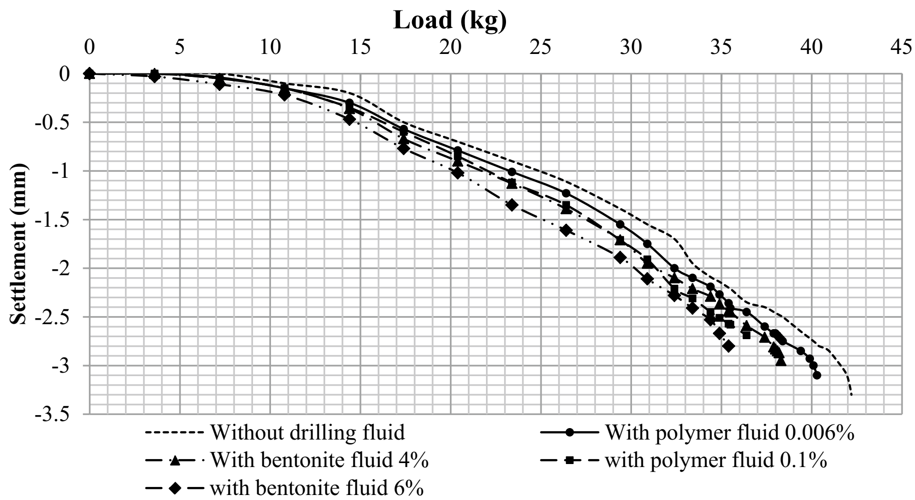

Fig. 3 Load-displacement curve for different bentonite and polymer concentrations as drilling fluid

Table 14 Experimental frictional resistance of model pile

Drilling fluid	Uplift capacity Q_{pe} (kN)	Weight of pile W_p (kN)	Frictional resistance P_{me} (kN)
No drilling fluid	0.41	0.0133	0.3967
0.006 % polymer	0.396	0.0127	0.3833
4 % bentonite	0.377	0.0131	0.364
0.1 % polymer	0.372	0.0130	0.359
6 % bentonite	0.348	0.0125	0.336

Frictional resistance of prototype concrete pile

The frictional resistance of model piles obtained from the pull out test was used to determine the K_{exp} by substituting result values in Eq. 1 and the results are presented in Table 15 for different cases. K tanδ in Eq. 1 is dependent on soil type and $\delta = \phi$, hence the constant C is only dependent of K, it is very difficult to get the correct value of K, hence the result of model pile test and direct shear test on soil and with different type of drilling fluid is used to find out the value of K. It is observed that the K value is coming out to be more than the coefficient of passive earth pressure, which is used in many case to find out the uplift capacity. As the uplift capacity of pile is directly proportional to K value and as $K_{exp} > K$, the actual uplift capacity will be more than that is calculated by

Table 15 Determination of K-Factor

Drilling fluid	Frictional resistance P_{me} (kN)	ϕ°	C ($K_{exp} \times \tan\delta$)	K_{exp}
No drilling fluid	0.3967	41.28	2.93	3.29
0.006 % polymer	0.3833	40.1	2.79	3.32
4 % bentonite	0.364	37.38	2.65	3.47
0.1 % polymer	0.359	37.07	2.62	3.46
6 % bentonite	0.336	32.68	2.44	3.81

Eq. 1. The use of K_{exp} instead of K will give not only safe but also the economical design of pile.

Now in the Eq. 1 K_{exp} is used for calculating the uplift capacity for pile with the use of different types of drilling fluid and without the use of drilling fluid, the results are tabulated in Table 16. The pile drilled in soil without use of bentonite and polymer for stabilizing the excavation is having the highest capacity but the effect of use of bore hole stabilizer is to reduce the uplift capacity the % reduction is more in case of bentonite than the polymer. It can be seen from the rheological properties of bentonite and polymer presented at Tables 1 and 2 respectively the 6 % bentonite and 0.006 % polymer both has given almost similar properties in terms of Marsh viscosity and comply with the requirement of drilling fluid in terms of Marsh Viscosity, but reduction in uplift capacity for the above dose in case of bentonite is 18.24 % as compared to 3.5 % in case of polymer.

Proposed K- factor

If we compare the theoretical and experimental frictional resistance of prototype pile, the theory predicts a safer value i.e. it underestimates the actual uplift capacity of pile. Thus a K-factor has been proposed comparing the results obtained from theoretical and experimental analysis. The K value can be active earth pressure coefficient, earth pressure coefficient at rest or passive earth pressure coefficient as quoted by various researchers, but K_{exp} as presented in Table 16 was found to be close to passive earth pressure coefficient. Thus K can be written as:

$$K = A_i \times K_p \tag{2}$$

where, K_p = Passive earth pressure coefficient, and calculated as $(1 - \sin\phi)$, A_i = A constant depends on ϕ value, called as A-factor, ϕ = Angle of internal friction.

The value of A_i factor for different angle of internal friction has been calculated and presented in Table 17 by substituting K = Kexp in Eq. 2.

The A_i value is dependent on ϕ and it can be taken from the graph proposed in Fig. 4. This factor when multiplied with the passive earth pressure coefficient gives K-value which may be used in Eq. 1 to obtain more approximate theoretical uplift capacity of the pile.

Table 16 Frictional resistance of prototype pile

Drilling fluid	K_{exp}	$\tan\delta = \tan\phi$	Frictional resistance P_{pe}	% reduction
No drilling fluid	3.29	0.877	1338.86	0.00
0.006 % polymer	3.32	0.842	1293.64	3.50
4 % bentonite	3.47	0.764	1228.16	9.01
0.1 % polymer	3.46	0.755	1211.62	10.50
6 % bentonite	3.81	0.641	1132.31	18.24

Table 17 Determination of A_i-factor

Drilling fluid	φ°	K_p	A_i
No drilling fluid	41.28	4.88	0.674
0.006 % polymer	40.1	4.62	0.719
4 % bentonite	37.38	4.09	0.848
0.1 % polymer	37.07	4.04	0.856
6 % bentonite	32.68	3.35	1.137

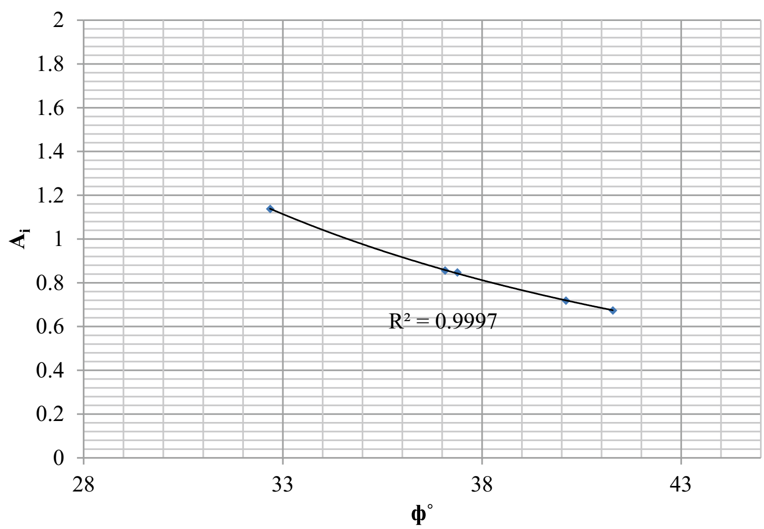

Fig. 4 Proposed of A_i-factor for different φ values

Conclusions

The use of bentonite and polymer for stabilizing the bore hole is investigated and it is found that a very small % of polymer is sufficient to stabilize the bore hole as compared to bentonite. The use of polymer also reduces the complete piling cycle as it does not require flushing of the bore before concreting. Direct shear test have been performed on the soil and by applying a layer of bentonite and polymer on shearing plane to see the effect of drilling fluid on frictional resistance of the soil and it is observed the effect of drilling fluid is to reduce the frictional resistance and the reduction is more in the case of bentonite than the polymer.

Physical modelling of pile is done to find out the uplift capacity of bored pile, for that modelled pile is bored without use of drilling fluid and by using different % of bentonite and different % of polymer separately and pull out test is performed on the fabricated test set up. The test results are compared with the theoretical uplift capacity suggested by [9]. It was observed uplift capacity is higher than the theoretical capacity, hence a modification factor is proposed based on the experimental study, which is multiplied to the theoretical equation to get the correct uplift capacity.

The results of pull out test indicate that pull out capacity is reduced by using bentonite or polymer in the boring fluid for stabilization of bore holes, but the reduction is more in case of bentonite than the polymer.

Authors' contribution
AKS, DJ and SV carried out the studies for finding out the benefit of use of polymer as compared to bentonite (which in use since long time) as a bore hole stabilizer for piling. The test results indicate that polymer increases not only the frictional resistance but also increases the pile load carrying capacity. It makes it economical, reduces the time required for piling operation and also environmental friendly. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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