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Closure to "Effect of Bentonite Slurry Pressure on Interface Friction of Pipe Jacking" by Mucahit Namli and Erol Guler

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The authors are thankful for such a beneficial discussion. It is impossible to have an undisturbed sample from sand so the density of the in situ sand was determined according to the standard penetration test (SPT) values and the sand sample was prepared in the laboratory at a similar density. Due to the difficulty of having undisturbed sample from sand, pipe jacking operation in sand should not be modeled in the lab alone. Hence, in the original paper both in situ and lab observations were recorded and analyzed together.

Before the beginning of our research, the optimum bentonite concentration was investigated in the lab. Then we made a laboratory study for observing the filtration pattern of the selected concentration of bentonite in sand.

For injection applications, there are three types of filtration patterns. The first one is surface filtration in which injection penetrates less than 40 mm, the second one is deep filtration in which injection penetrates between 40 and 50 mm, and the third one is rheological blocking in which the injection depth is longer than 1 m. But it has not yet understood which one of these is most effective in pipe jacking.

Both to investigate filtration pattern and to investigate the bentonite injection mechanism, two new lab test setups were prepared in the Boğaziçi University Geotechnical Lab. In this PhD study (Namli 2011), three stages of laboratory investigation were performed related to pipe jacking. The first stage of tests was bentonite injection into sand. The aim of the bentonite injection test was to determine the optimum concentration of sodium bentonite slurry and to understand which factors affect the stability of bentonite slurry. In the second stage, the interface friction of sand and concrete was researched through a shear box test on the samples taken from the tests performed in the first stage. In the third stage, the optimum injection pattern was investigated in addition to measuring the interface friction coefficient of sand and concrete sample without bentonite and with bentonite.

Laboratory Tests on Bentonite Injection in Sand

In order to investigate the injection of bentonite slurry in sand during pipe jacking, a test setup as shown in Fig. 1 was prepared. The plexiglass cell was 10.5 cm in diameter and it was filled with 20-cm-high sand. At the beginning, sand was saturated with water to represent the case below the water table. Then 5-cm-high bentonite slurry was poured on the saturated sand and pressure on the bentonite slurry was raised every 5 min with steps of 25–400 kPa (Fig. 1).

Different concentrations of bentonite slurries with different waiting times were observed by measuring their first and last marsh viscosity (Table 1). The same bentonite and sand were used in all the tests. Properties of the sand used in the test are given in Table 2. The internal friction angle of the sand used in the test was found as Ø = 30° from the direct shear test.

According to EN ISO 13500 (ISO 2008), the apparent viscosity of the bentonites (fan viscosity) reading at 600 rpm should be higher than 0.03 Pa · s (30 cP). The filtration volume between

Fig. 1. Bentonite injection in sand test setup. (Image by Mucahit Namli.)

Table 1. Marsh funnel viscosity readings

Reading	Bentonite amount in 1 L water			
	30 g	40 g	50 g	60 g
Marsh viscosity after preparation	30 s	34 s	41 s	62 s
Marsh viscosity after 24 h	32 s	38 s	54 s	120 s
Bleeding water after 24 h	18%	10%	5%	0%

Source: Adapted from Namli (2011).

Table 2. Properties of sand used in bentonite injection test

Property	Value
Unit weight, γ (kN/m^3)	15.8
Specific gravity of solid constituents, G_s	2.59
Effective grain size, D_{10} (mm)	0.31
Uniformity coefficient, C_u	3.23
Coefficient of curvature, C_c	1.32

Source: Adapted from Namli (2011).

Table 3. Rheological parameters of bentonite used

Parameter	Value
Type of bentonite	Sodium bentonite
Cation exchange capacity	70 meq/100 g
pH	9.9
Moisture	10%
Apparent fan viscosity (600 rpm)	54 cP
Plastic viscosity (600–300 rpm)	4 cP
Filtration volume	14 mL
Swelling volume (for 2 g bentonite after 24 h)	29 mL

Source: Adapted from Namli (2011).

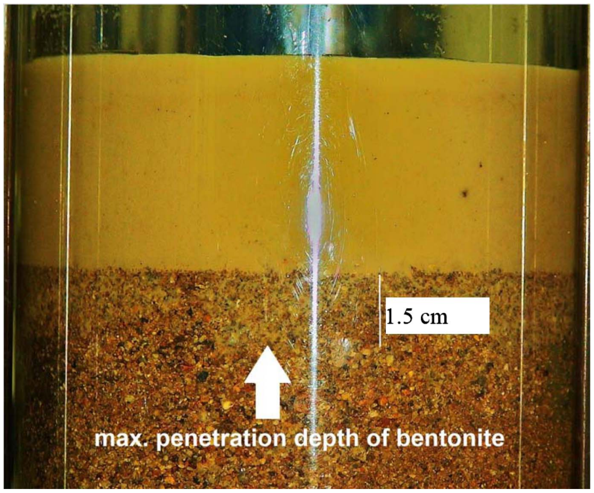

Fig. 2. Bentonite injection after 24 h of hydration. (Image by Mucahit Namli.)

7.5 and 30 min in the filter press test should be less than 15 mL. The definition of rheological parameters are as follows:

- Apparent viscosity = 600 rpm fan viscosity reading;
- Plastic viscosity = 600–300 rpm; and
- Yield point = 300 rpm–plastic viscosity.

Rheological parameters of the sodium bentonite used in the laboratory test was measured at Istanbul Technical University Mining Faculty, Mineral Processing Engineering Department, Surface Chemistry Laboratory. These parameters are summarized in Table 3.

Fifteen tests were performed with different bentonite concentrations in the first stage of laboratory tests. As a result, it was observed that the optimum concentration of bentonite in order to obtain a stable slurry is 6% bentonite by weight in water. Bentonite slurry should wait at least 1 day for hydration. For the sand that has effective particle diameter (D_{10}) of 0.32 mm used in the first stage of laboratory tests, it can be said that the filtration result was observed as surface filtration as can be seen in Fig. 2. If waiting duration is not adequate for hydration, loss of bentonite becomes too much (Fig. 3), which means bentonite slurry penetrates the sand and cannot provide the required function.

After the filtration observation tests, the concentration of 6% bentonite slurry that has a Marsh funnel viscosity after 24 h of 120 s was used in the next part of the study.

Interface Coefficient between Concrete and Sand with and without Bentonite Interface

In this second stage, the interface coefficients between dry sand and concrete before and after bentonite injection were compared.

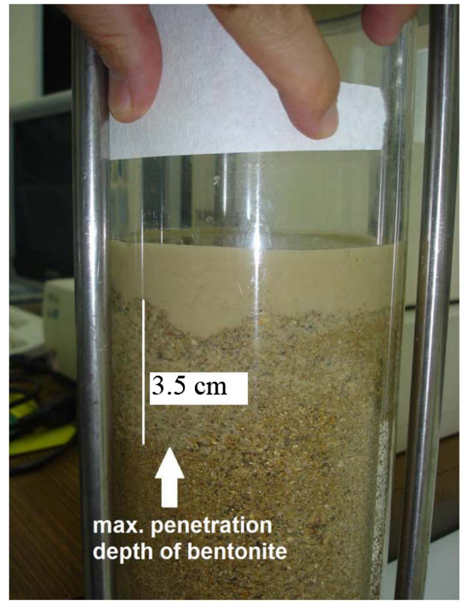

Fig. 3. Bentonite injection just after preparation. (Image by Mucahit Namli.)

For this comparison, the soil sample taken from the top contact zone of sand and bentonite slurry after the injection test and the concrete prepared at the lab were used in the shear box test. At the end of the shear box tests, the interface friction coefficient between dry sand and concrete was measured as $\mu_{\text{int}} = 0.90$. The interface friction coefficient between dry sand and concrete after bentonite was injected was measured as $\mu_{\text{int}} = 0.46$. This means that a 50% reduction has been achieved.

From the shear box results and bentonite injection tests, it was observed that even though bentonite slurry was not applied with pressure between concrete and soil, the interface friction coefficient μ_{int} between sand and concrete $\mu_{\text{int}} = 0.90$ reduced to $\mu_{\text{int}} = 0.46$ after bentonite was placed between concrete and sand. This reduction percent is comparable to the decrease of friction forces after bentonite injection measured at the real in situ projects.

In Reilly and Orr (2017), the tests were performed without taking into consideration the filtration pattern. The methodology of bentonite sample preparation in Reilly and Orr (2017) is far from representing the application at a job site, so a direct shear test cannot be said to represent the field application appropriately. Compared with the study of Reilly and Orr, where the Marsh viscosity was 40 s, it is obvious that viscosity of the authors' bentonite slurry was much higher than the discussers'.

In Situ Measurements

From the measurements made during real pipe jacking projects, it was observed that if the bentonite slurry is applied after the increase of frictional forces, it can cause a decrease in the coefficient of friction up to half of the case with no bentonite. Such reductions were observed during the Goksu River 6–8 drive and Tuzla River 5–6 drive (Figs. 4 and 5, respectively).

The vertical stress on the pipe was calculated according to Terzaghi's trapdoor model. The coefficient of reduction was taken from Fig. 6 and the meanings of symbols are as follows:

1. $\sigma_\nu = \kappa \cdot \gamma h$ (t/m^2) where
   - σ_ν = vertical stress on pipes;
   - κ = reduction coefficient depending on ratio of h/de;

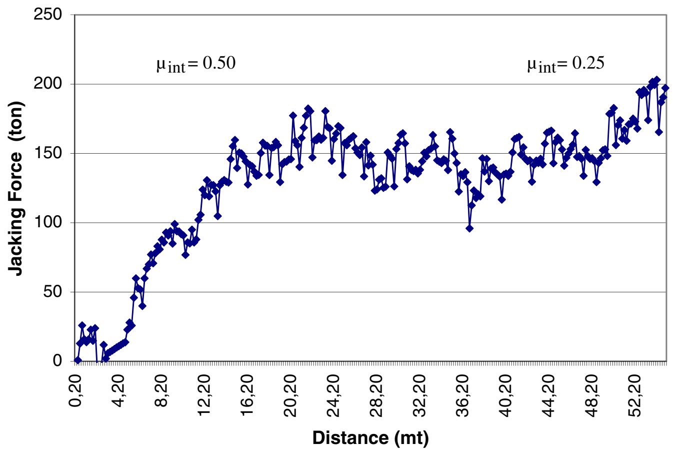

Fig. 4. Goksu River 6–8 drive.

- h = height of cover; and
- de = external pipe diameter.

2. L = length of drive;
3. τ = friction (resistance) stress;
4. μ_{int} = coefficient of friction;
5. F_T = total force;
6. F_{face} = penetration force;
7. F_{net} = net friction force (net frictional part of jacking force), $F_{net} = F_T – F_{face}$ (t), $\tau = F_{net}/(\pi \times de \times L)$ (t/m^2); and
8. $\mu_{int} = \tau/\sigma_\nu$.

For Fig. 4, the Goksu River between Pits 6 and 8:
Before bentonite injection:

- Distance between 0 and 22 m, $L = 23$ m;
- $h = 3$ m; $de = 1,7$ $h/de = 2- \rightarrow$ from Fig. 6, $\kappa = 0.47$;
- $\gamma = 1.8$ t/m^3;
- $\sigma_\nu = \kappa \cdot \gamma \cdot h = 0.47 \times 1.8 \times 3 = 2.54\,\text{t/m}^2$;
- $F_{net} = 182 - 26 = 156$ t;
- $\tau = F_{net}/(\pi \times de \times L) = 156/(3.14 \times 1.7 \times 23) = 1.27$ t/m^2; and
- $\mu_{int} = \tau/\sigma_\nu = 1.27/2.54 = 0.5$.

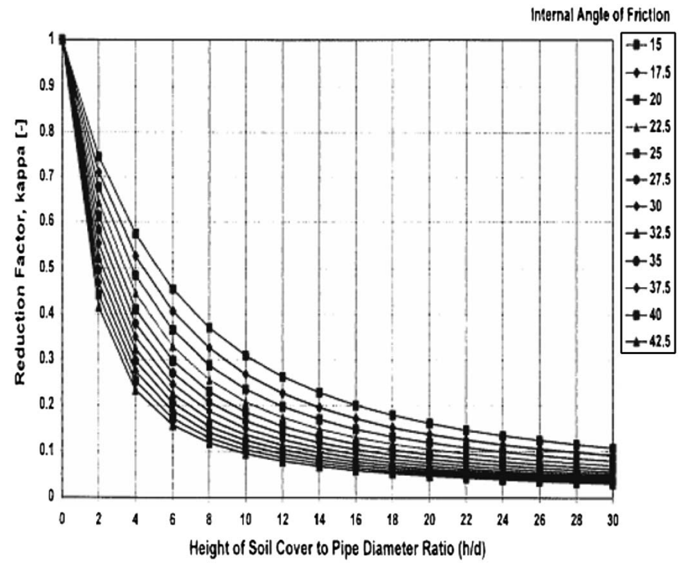

Fig. 6. Reduction factor as a function of height of soil cover to pipe. (Reprinted from Staheli 1996, with permission.)

Goksu River between Pits 6 and 8 for last 20 m:
After bentonite injection:

- $L = 20$ m;
- $F_{net} = 200 - 135 = 65$ t;
- $\sigma_\nu = 2.54$ t/m^2;
- $\tau = F_{net}/(\pi \times de \times L) = 65/(3.14 \times 1.7 \times 20) = 0.61$ t/m^2; and
- $\mu_{int} = \tau/\sigma_\nu = 0.61/2.54 = 0.25$.

For Fig. 5, Tuzla River between Pits 5 and 6:
Distance between 0 and 78 m:

- $\gamma = 1.8$ t/m^3; $L = 78$ m; $h = 8$ m;
- $de = 1.7$ m; $h/de = 4.7- \rightarrow$ from Fig. 6, $\kappa = 0.2$;
- $\sigma_\nu = \kappa \times \gamma \times h = 0.2 \times 1.8 \times 8 = 2.88$ t/m^2;
- $F_{net} = 420 - 50 = 370$ t;
- $\tau = F_{net}/(\pi \times de \times L) = 370/(3.14 \times 1.7 \times 78) = 0.89$ t/m^2; and

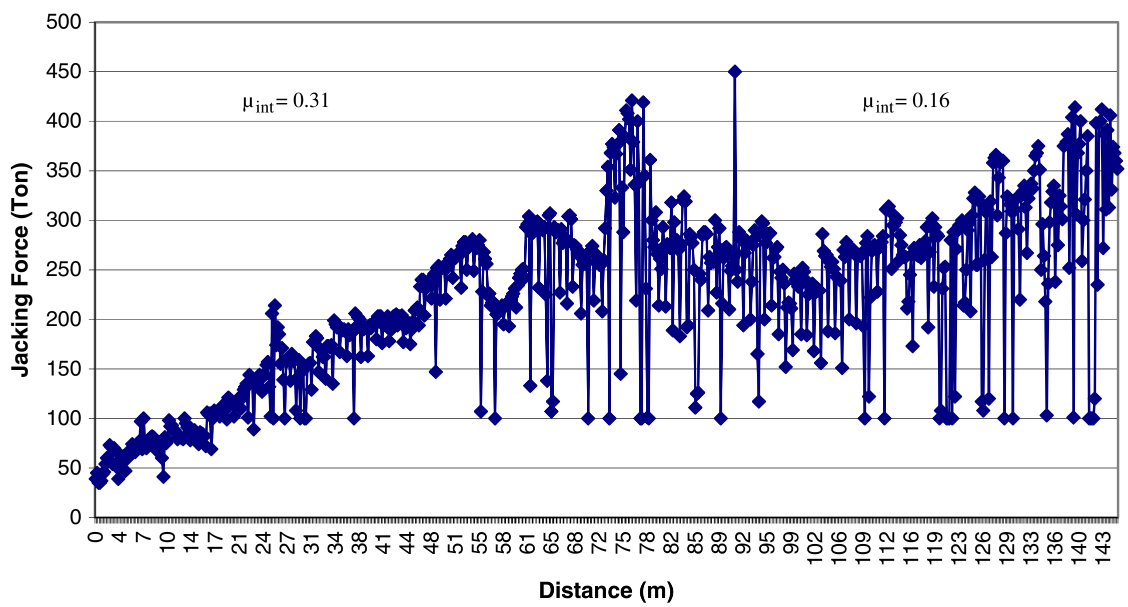

Fig. 5. Tuzla River 5–6 drive.

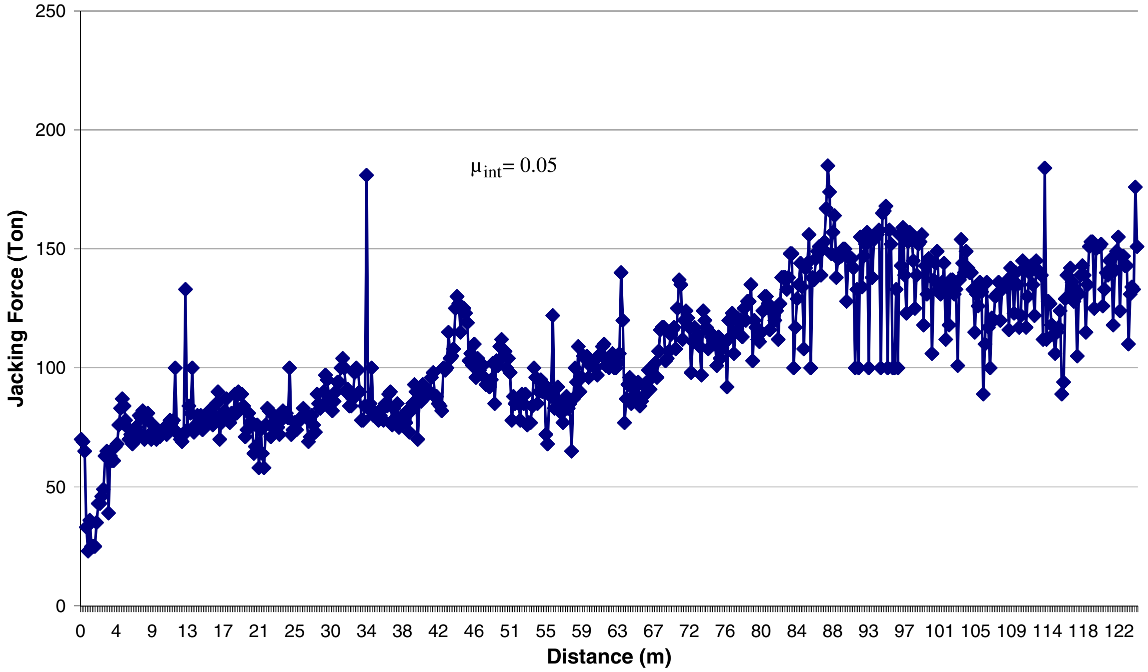

Fig. 7. Tuzla River 7–8 drive.

- $\mu_{\text{int}} = \tau/\sigma_\nu = 0.89/2.88 = 0.31$.
  Distance between 78 and 144 m:
- $\gamma = 1.8\ \text{t/m}^3$; $L = 66$ m; $h = 8$ m;
- $F_{\text{net}} = 420 - 250 = 170$ t;
- $\tau = F_{\text{net}}/(\pi \times de \times L) = 170/(3.14 \times 1.7 \times 66) = 0.48\ \text{t/m}^2$; and
- $\mu_{\text{int}} = \tau/\sigma_\nu = 0.48/2.88 = 0.16$.

It was also observed that the friction only reduces at the newly excavated zones and the frictional forces already developed between sand and pipe do not reduce. This shows that the bentonite cannot intrude in between the pipe and sand to reduce the friction once the sand comes into full contact with the pipe. On the other hand, if bentonite slurry injection starts with excavation and goes constantly parallel to excavation, the coefficient of friction may decrease to 10% of the case without bentonite (Fig. 7).

For Fig. 7, the Tuzla River between Pits 7 and 8:

- $\gamma = 1.8\ \text{t/m}^3$; $L = 122$ m; $h = 5$ m;
- $de = 1.7$ m; $h/de = 2.9 - \rightarrow$ from Fig. 6, $\kappa = 0.4$;
- $\sigma_\nu = \kappa \times \gamma \times h = 0.41 \times 1.8 \times 5 = 3.6\ \text{t/m}^2$;
- $F_{\text{net}} = 143 - 23 = 120$ t;
- $\tau = F_{\text{net}}/(\pi \times de \times L) = 120/(3.14 \times 1.7 \times 122) = 0.19\ \text{t/m}^2$; and
- $\mu_{\text{int}} = \tau/\sigma_\nu = 0.19/3.6 = 0.05$.

Conclusion

As a result of laboratory tests, the measurements made for real pipe jacking projects, and site experience of the authors, the writers' conclusion is that the statement "the bentonite slurry which has appropriate concentration blocks the pores in the soil and, with the pores blocked, this allows the fluid pressure within the slurry to be transferred to the soil skeleton (Reilly and Orr 2017)" is not adequate to understand the reality at the jobsite.

If bentonite slurry is applied directly between sand and pipe, the coefficient of friction reduces to almost 10% of the direct sand–concrete friction. If bentonite slurry is not applied in time and is placed between concrete surface and sand, it will not serve the purpose of friction reduction fully. In other words, after the collapse of sand on the pipe and soil and concrete establishing full contact, pressurized bentonite application to the interface could not decrease friction forces down to 10%.

The methodology of bentonite sample preparation in Reilly and Orr (2017) is far from representing the application at the jobsite, so a direct shear test cannot be said to represent the field application appropriately. Therefore, we believe that the results given by Reilly and Orr (2017) are not in full agreement with this paper because they applied the bentonite injection after the concrete and sand were in touch already.

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