Measuring energy in dynamic probing

Ibáñez, S.J.
INGITER S.L.-University of Burgos, Burgos, Spain

Sagaseta, C.
University of Cantabria, Santander, Spain

López, V.
INGITER S.L.-University of Burgos, Burgos, Spain

ABSTRACT: The penetration in these tests is intimately related to the potential energy of the hammer (nominal energy). So, it is necessary to understand correctly and deeply how this energy is transferred to the drive rods and how it is transmitted through the rods to the cone, to realize how the real behavior in these tests is. The penetration length really depends on the energy, not on that nominal energy, but on a portion of that energy that is effectively transferred to the rods (*ENTHRU*) and, in order to be more precise, the energy that reaches the cone ($ENTHRU_{cone}$). The *ENTHRU* is measured by means of monitoring the upper part of the drive rods (close to the anvil). To calculate the $ENTHRU_{cone}$ it is necessary to correct the *ENTHRU* in three ways. First it is needed to take into account the energy loss in the energy transmission through the rods, and the energy loss due to the skin friction of the drive rods with the soil around them. It is also necessary to add the energy due to the rod weight that is penetrating into the soil.

KEY WORDS: dynamic, penetration, energy, DPSH

1 INTRODUCTION

There are different kinds of penetration tests. First of all, we have the Standard Penetration Test (SPT), maybe the most widespread penetration test. There is lot of literature about measuring energy in these kind of tests. However, there are many other penetration tests that differ a lot from SPT. They are called dynamic probing (DPH, DPSH…).

The SPT tests are performed into a borehole with a sampler, meanwhile dynamic probing tests are performed from the surface with a cone. So the main difference is quite clear: the friction between the drive rods and the soil around them.

2 ENERGY EFFICIENCY FOR SPT

Several authors have studied and measured the SPT energy. In this paper we will use one of the latest investigations by Odebrecht & Schnaid, et al (2005).

Housel (1965) was the first who used the word *ENTHRU*, that is the maximum energy transmitted to the rod stem. The *ENTHRU* was measured by means of integrating signals from some accelerometer and some strain gauges located below the anvil, as usual for these kinds of tests.

Odebrecht & Schnaid, et al (2005) found that this *ENTHRU* could be fitted to this equation:

$$ENTHRU = \eta_1 \cdot m_h \cdot g \cdot (h + p) \quad (1)$$

where η_1 = hammer efficiency factor; m_h = hammer mass; g = gravity acceleration; h = height of fall (free fall of the hammer after being released); and p = penetration for one blow.

After analyzing the data from the tests, the value of η_1 was calculated as 0.765.

Odebrecht & Schnaid, et al (2005) also inferred the value of the computed sampler energy ($E_{sampler}$). The sampler energy is the value of the actual energy that reaches the sampler.

$$E_{sampler} = \eta_3 \cdot [\eta_1 \cdot m_h \cdot g \cdot (h + p) + \eta_2 \cdot m_r \cdot g \cdot p] \quad (2)$$

where η_3 = energy efficiency factor; η_2 = rod efficiency factor; and m_r = rod mass.

The experimental data were adjusted and the proposed values for the efficiency factors were:

$$\eta_3 = 1 - 0.0042 \cdot l \quad (3)$$

where l = rod length.

The value of η_2 equals 1.

3 DIFFERENCES BETWEEN SPT AND DYNAMIC PROBING

Both kinds of tests are quite similar but there are some differences that will have to yield to different ways of measuring the energy.

The SPT tests are carried out with a sampler that is driven into the soil so, after the tests there is a recovered disturbed sample. The dynamic probing tests use a cone, instead of a sampler. This cone may be either retained (fixed) for recovery or disposable (lost).

Even though both tests are quite similar, in terms of analyzing the energy, there is a mayor difference. As the SPT tests are undertaken inside a borehole there is no friction between the drive rods and the soil around them, whereas in dynamic probing, as the cone is not much wider than the rods, such friction exists.

4 MEASURING THE LATERAL FRICTION

The drive rods and the cone will be driven vertically in order to avoid such lateral friction.

The rods will be rotated 1.5 turns or until maximum torque is reached at least every 1 m penetration. The aim of this rotation is to tighten the rod conections and to reduce the skin friction.

Every dynamic probing equipment has a torque measuring device. It is usually a torque wrench or similar measuring device. The rods will be rotated by means of this device so, at the same time, we get the value of the maximum torque.

The frictional force F_f, necessary to rotate the drive rods, is calculated with the skin resistance, and the lateral area of the drive rods.

$$F_f = \tau \cdot 2 \cdot \pi \cdot r \cdot l \tag{4}$$

where τ = skin friction resistance; r = rod radius; and l = rod length.

The maximum torque necessary to rotate the drive rods will be the frictional force multiplied by the force arm.

$$T = F_f \cdot r = \tau \cdot 2 \cdot \pi \cdot r^2 \cdot l \tag{5}$$

where T = maximum torque.

This way, the value of the skin friction is calculated in Equation 6 below:

$$\tau = \frac{T}{2 \cdot \pi \cdot r^2 \cdot l} \tag{6}$$

The energy used to overcome the friction between the drive rods and the soil around them, during the penetration, (frictional energy E_f) could be calculated with the Equation 7 below:

$$E_f = F_f \cdot p \tag{7}$$

Substituting the value of F_f from Equation 4 in Equation 7:

$$E_f = \tau \cdot 2 \cdot \pi \cdot r \cdot l \cdot p \tag{8}$$

And using the value of the skin friction from Equation 6, we get the final Equation 9 below:

$$E_f = \frac{T \cdot p}{r} \tag{9}$$

This Equation 9 was obtained by Dahlberg & Bergdahl (1975).

The aforementioned equation only works assuming that the semi static skin friction during rotation of the drive rods is the same as the dynamic skin friction during penetration.

Due to this difference between skin friction in static and dynamic process, Bergdahl (1979) calculated the part of the total number of blows in a SPT test, that was "used" to overcome that lateral friction. When he calculated that N, he did not divide it by the energy efficiency, so he was really multiplying that N by the energy efficiency. This way, he realized that the energy due to lateral friction was the same energy as the calculated in Equation 9, but with a factor of 3.4 and multiplying by the energy efficiency. This means that the dynamic lateral friction resistance in the vertical direction during driving is much greater than the semi static resistance in the horizontal direction during turning of the rods.

This way, we can consider the next equation to get that frictional energy:

$$E_f = \frac{T \cdot p}{r} \cdot 3.4 \cdot \eta \tag{10}$$

where η = energy efficiency.

This efficiency means the percentage out of the nominal energy that really reaches down to the cone.

The nominal energy is defined as the hammer weight multiplied by the height of fall.

From now on, it is defined $ENTHRU_{cone}$ as the real amount of energy that effectively reaches the cone. It is the equivalent to what Odebrecht & Schnaid, et al (2005) called $E_{sampler}$ in a SPT test.

$$E_f = \frac{T \cdot p}{r} \cdot 3.4 \cdot \frac{E_{sampler}}{m_h \cdot g \cdot h} \tag{11}$$

5 $ENTHRU_{CONE}$ IN DYNAMIC PROBING

Using the $E_{sampler}$ in a SPT (Equation 2) as part of the new $ENTHRU_{cone}$, we only need to substract that part of the *ENTHRU* that is used to overcome that skin friction (E_f). Thus, we get the Equation 12:

$$ENTHRU_{cone} = E_{sampler} - E_f \tag{12}$$

By substituting the value of $E_{sampler}$ (Equation 2) and the value of E_f (Equation 11) in Equation 12:

$$ENTHRU_{cone} = \eta_3 \cdot [\eta_1 \cdot m_h \cdot g \cdot (h+p) + m_r \cdot g \cdot p] \cdot$$

$$\cdot \left[1 - \frac{T \cdot p \cdot 3.4}{r \cdot m_h \cdot g \cdot h}\right] \quad (13)$$

The value of m_r is the mass of the rods that includes the anvil mass. We can write the Equation 13:

$$ENTHRU_{cone} = \eta_3 \cdot [\eta_4 \cdot m_h \cdot g \cdot (h+p) + m_a \cdot g \cdot p +$$

$$+ m_r \cdot g \cdot p] \cdot \left[1 - \frac{T \cdot p \cdot 3.4}{r \cdot m_h \cdot g \cdot h}\right] \quad (14)$$

where m_a = mass of the anvil where the hammer strikes when falling down; and η_4 = energy efficiency factor.

The *ENTHRU* measured just below the anvil is:

$$ENTHRU = \eta_4 \cdot m_h \cdot g \cdot (h+p) + m_a \cdot g \cdot p \quad (15)$$

Equation 14 could be rewritten as:

$$ENTHRU_{cone} = \eta_3 \cdot [ENTHRU + m_r \cdot g \cdot p] \cdot$$

$$\cdot \left[1 - \frac{T \cdot p \cdot 3.4}{r \cdot m_h \cdot g \cdot h}\right] \quad (16)$$

This different way of measuring the *ENTHRU* makes different η_1 from η_4. Therefore, in dynamic probing we can not assume the value of η_4 as 0.765 as in Odebrecht & Schnaid, et al (2005). This fact will be treated further.

The value of η_3, obtained from Equation 3 is going to be changed. It would be better if this factor had no units, so this factor is changed to a non dimensional factor.

If the last part of this factor is multiplied and divided by the rod diameter:

$$\eta_3 = 1 - 0.0042 \cdot l \cdot \frac{d}{d} \quad (17)$$

where d= rod diameter.

The rod diameter used by Odebrecht & Schnaid, et al (2005) was the normal diameter for SPT drive rods whose value is 2.28 x 10^{-2} m.

$$\eta_3 = 1 - 0.0042 \cdot l \cdot \frac{2.28 \cdot 10^{-2}}{2 \cdot r} = 1 - 4.8 \cdot 10^{-5} \cdot \frac{l}{r} \quad (18)$$

6 FIELD WORK

Several tests were conducted using an instrumented rod in dynamic probing, in order to calculate the value of η_4 and to find out if this value is about 0.765, as Odebrecht & Schnaid, et al (2005) calculated for SPT.

6.1 *Instrumentation*

The top part of the rods was instrumented by means of four strain gauges and two accelerometers as it can be observed in Figure 1.

The instruments were located 32.6 x 10^{-2} m below the point of contact between the hammer and the anvil. This length was chosen in compliance with EN ISO 22476-2:2005. It is necessary that the instrumented section of rod is positioned at a distance greater than 10 times the rod diameter below the point of hammer impact on the anvil.

Each of the four strain gauges was fixed and attached to the rod, and was independent from the rest of the strain gauges. They were assembled as 4 different quarter Wheatstone bridges.

The two ICP piezoelectric accelerometers were mounted diametrically opposite on little steel pieces that were bolted to the rod. The accelerometers were suitable up to 10,000 g accelerations.

The signal conditioner/amplifier used in this research was the SCADAS III signal acquisition equipment, model SC 316 front-end system (LMS Difa Instruments Company).

The digital conversion of the data was design oversampling at a rate of 25,600 Hz. This way, the final representation of the data was at a rate of 10,000 Hz.

Figure 1. Instrumented portion of the rod string with the strain gauges and the accelerometers.

6.2 *Site*

The field work was conducted at Arija, at the northern part of Burgos, Spain.

The soil consists of a thick layer of sand, being classified as SP in compliance with the USCS classification.

This place was chosen because it consisted of a very homogeneous thick sandy layer. The soil surface was very horizontal and it was easy to access with all the equipment (penetrometer on wheels, bars and vehicle).

In the Figure 2 below it is shown the location of this site. In this figure it is shown the location in Spain and an orthophoto.

Figure 2. Location and orthophoto (SIGPAC).

6.3 *Experimental results*

More than 200 tests were performed at the site explained above.

The value of *ENTHRU* was measured by integrating the signals from the instrumented rod.

Then, the value of η_4 was calculated by using the Equation 15. This efficiency factor can be expressed in the following form:

$$\eta_4 = \frac{ENTHRU - m_a \cdot g \cdot p}{m_h \cdot g \cdot (h + p)} \qquad (19)$$

The values obtained from the field work are shown in Table 1.

As it is revealed in this table, the values show large scattering.

Table 1. Values of the energy efficiency factor obtained from the tests carried out

Series	Number of data tests	Energy efficiency factor (η_4) (average values)
1	44	0.681
2	39	0.688
3	27	0.718
4	17	0.739
5	37	0.774
6	38	0.771

We can conclude that this value (η_4) is not the same as the value of η_1. As the value of η_4 shows such dispersion, it is assumed the need of measuring the *ENTHRU* instead of calculating it from the Equation 15.

7 CONCLUSIONS

The way of measuring energy in SPT is different from dynamic probing. The main difference is the skin friction between the drive rods and the soil around them.

It is necessary to use the $ENTHRU_{cone}$ instead of using the *ENTHRU*. The reason is that the energy that really produces penetration is the part of the total energy that effectively reaches the tip of the cone below the rod string.

In order to calculate this $ENTHRU_{cone}$ it is proposed a new equation (Equation 16). For being able to calculate $ENTHRU_{cone}$ in a right way, it is necessary to measure the *ENTHRU* by means of an instrumented rod. It is not enough accurate to calculate *ENTHRU* with Equation 15, because of the wide range or possible values of the energy efficiency factor.

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