Indian Geotechnical Journal, 39(2), April 2009, 227 - 239

TECHNICAL NOTE

Pile Driveability Analysis using GRLWEAP

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Introduction

The tremendous increase in the use of piles for both onshore and offshore structures and the development of new pile driving methods have created more interest in devising more reliable methods for analysis and design of piles. Capacity of a pile is one of the important aspects which is required to be taken into account while analyzing and designing the piles.

Perhaps the oldest and most frequently used method of estimating the load capacity of driven piles is to use a driving formula or dynamic formula. All such formulas relate the ultimate load capacity to the pile set (the vertical movement per blow of the driving hammer) and assume that the driving resistance is equal to the load capacity of the pile under static loading. They are based on idealized representation of action of the hammer on the pile in the last stage of its embedment. There are a great number of driving formulas available of varying degrees of reliability. The primary objectives in using pile driving formula are usually either to establish a safe working load for a pile by using the driving record of the pile or to determine the driving requirements for a required working load. The working load is usually determined by applying a suitable safety factor to the ultimate load calculated by the formula. This safety factor, however, varies considerably depending on the formula used and the type of pile being driven.

A relatively recent improvement in the estimation of load capacity by dynamic methods has resulted from the use of the wave equation to examine the transmission of compression waves down the pile, rather than assuming that a force is generated instantly through out the pile, as is done in deriving driving formulas. Themain objective in using the wave equation approach is to obtain a better relationship between ultimate pile load and pile set than can be obtained from a simple driving formula. In addition to providing a means of load capacity estimation, this relationship allows an assessment to be made of the driveability of a pile with a particular set of equipment. Moreover, this approach also enables a

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rational analysis to be made of the stresses in the pile during driving and can therefore be useful in the structural design of a pile.

The aspect of the conventional dynamic formulas and the concept of the wave equation and its subsequent refinement by various researchers thereby replacing the dynamic formulas are briefly reviewed in the subsequent section.

Brief Review of Literature

Dynamic Formulas

A pile driving formula is an attempt to evaluate resistance of pile to dynamic forces applied upon it during driving and to estimate further static longitudinal load that the pile can support safely as a part of permanent structure [Dunham (1954)]. The pile driving analysis takes into account the fact that each hammer blow produces a stress wave that moves down the length of the pile at the speed of the sound so that the entire length of the pile is not stressed simultaneously as assumed in the conventional dynamic formulae.

The method of determining the ultimate capacity of piles was introduced by Sanders in 1850 by equating the energy imparted by the falling weight and the resistance to penetration of the pile during the last few blows (termed set). Pointing out the pile driving formula suggested by Sanders did not take into account the energy losses Wellington in the year 1898 slightly modified the formula devised by Sanders. The formula suggested by Wellington came to be known as Engineering News Formula and is still being used by some of the researchers. It was improved by Hiley in 1925 as Hiley formula. His contribution was in the identification of the various components of C (the parameter corresponding to the temporary compression due to hammer blow) introduced by Wellington. In 1953 Janbu reported an energy analysis of pile driving with the use of dimensionless parameters and proposed a formula similar to the one devised by earlier researchers. Another formula commonly used in India is the Simplex Formula. [Varghese (2005)].

Wave Equation

It was around 1950 that E.A.L. Smith, a mechanical engineer working with Raymond Pile Co., first suggested the use of wave equation analysis for analyzing the problems in piles. Basically, the wave equation is used to describe how stress waves are transmitted in a long rod when a force is applied at one end of the rod.

Smith (1960) proposed a numerical solution to investigate the effects of factors such as ram weight, ram velocity, cushion and pile properties and dynamic behavior of soil during driving. Based on the studies carried out over a period of a decade, he proposed a simple equation derived in the context of pile – hammer-soil system illustrated in Figure 1. Since then, several researchers worked on the theme postulated by Smith (1960) and tried to bring it in the refined form. Unlike other conventional pile driving formulae, the wave equation analysis is suitable for piles in all types of soils.

Realizing the difficulty in working out the wave equation analysis by hand calculations, efforts were made in the decade of 1970 for computerization of the

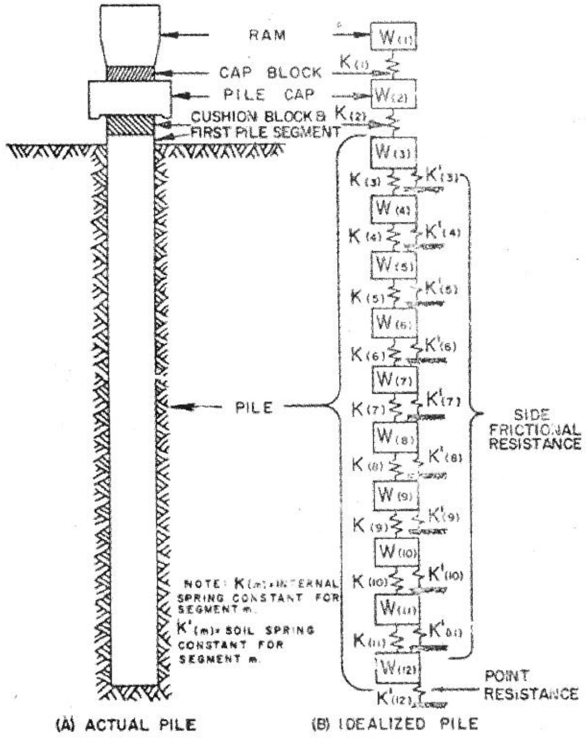

Fig. 1 Idealization of a Pile-soil System for the Purpose of Analysis

analysis. Based on the theory of wave equation postulated by Smith (1960) many prominent researchers worked on the aspect of conventional pile driveability analysis and computerization of the solution. The significant works reported on the pile driveability analysis include that by Bowles (1974), Gobble et al (1975), Gobble and Rausche (1976), Desai and Christian (1977), Gobble and Rausche (1979), Gobble et al (1980), Gobble and Rausche (1981), Gobble and Hery (1984), Gobble and Abou- matar (1992), Rausche et al (1992), Hussein et al (1992), Likins et al (1996), Rausche et al (2000), Rausche et al (2004) and Hussein et al (2006).

More refined general purpose programs that are available in market nowadays and which can handle many more variables involved in the pile driveability analysis include CAPWAP (1975) [Case Analysis of Piles by Wave Analysis of Piles], WEAP (1976) [Wave Equation Analysis of Piles], GRLWEAP (1998, 2005)

Scope of the Present Work

From the above review of literature it is observed that the basic concept of Wave Equation Analysis of Piles postulated by Smith (1960) was further extended by other researchers and many analytical and computational methods were devised. This further led to the development of various software programs capable of solving the problem of pile driveability analysis. The present paper reports the pile driveability analysis based on one such software program, i.e., GRLWEAP (Version 2005).

The following section gives the brief overview of the method of Wave Equation Analysis of Piles (WEAP) suggested by Smith (1960) and GRLWEAP analysis program used in the present study.

Smith's Analysis (1960)

Smith proposed a solution based on concentrating the distributed mass of the pile into a series of small weights, connected by weightless springs with the addition of soil resistance acting on the masses, as illustrated in Figure 1. Time was also divided into small increments. Many of the assumptions made by Smith (1960) especially for modeling the soils had a minimum theoretical backing. Nevertheless, the soil model proposed by him is still used as the standard one in many wave equation programs being developed even today..

Smith proposed the following simple equations for the pile – hammer – soil system shown in Figure 1.

$$D(m,t)= D(m,t-1)+\Delta t.v(m,t-1) \tag{1}$$

$$C(m,t)=D(m,t)-D(m+1,t) \tag{2}$$

$$F(m,t)=C(m,t).K(m) \tag{3}$$

$$R(m,t)=\left[D(m,t)-D'(m,t)\right].k'(m).\left[1+J(m).V(m,t-1)\right] \tag{4}$$

$$V(m,t)=V(m,t-1)+\begin{bmatrix} F(m-1,t)+W(m)- \\ F(m,t)-R(m,t) \end{bmatrix}.\frac{g\Delta t}{W(m)} \tag{5}$$

where,

m = element no, t = time and Δt = time interval

C(m,t) = compression of internal spring, m at time, t

D(m,t) = displacement of element m at time, t (total)

D'(m,t) = plastic displacement of external spring, m at time, t

F(m,t) = force in internal spring, m at time, t

g = acceleration due to gravity

J(m) = soil damping constant at element, m

k(m)= spring constant for internal spring, m (pile) *k'(m)* = spring constant for external spring, m (soil)

R(m,t) = force exerted by external spring, m on element, m at time, t (soil resistance)

v(m,t) = velocity of element, m at time, t

The above equations are solved for each of the pile elements involved for a succession of time intervals, starting when the hammer travelling with known velocity touches the first spring. The solution continues until the permanent set or plastic displacement of the soil at the tip is maximum.

The basic steps involved in the numerical solution of wave equation are given below.

1. The velocity of the top weight is set equal to the initial velocity of the pile-driving ram at the instant of impact.
2. A short time interval, t is permitted to elapse (of the order of 1/5000 second).
3. The ram velocity is assumed to be uniform during this time interval and a new position of the ram is calculated.
4. Since the velocities of all other weights are zero, their displacements after the elapse of the first time interval will remain zero.
5. Because of the movement of the ram during the first time interval, the top spring is compressed and the resulting force is calculated from the spring constant for that spring.
6. The force developed in the cap block acts between the ram and the helmet. This unbalanced force tends to reduce the downward velocity of the ram and to increase the velocity of the helmet from zero. New ram and helmet velocities are calculated, the other weight velocities still being zero.
7. A second time interval is permitted to elapse.
8. Assuming that the new ram and helmet velocities are uniform during the second elapsed time interval, their new displacements are calculated. These new displacements result in new spring compressions in the first and second springs from which new spring forces may be computed. This result in unbalanced forces on the first three weights and new velocities for these weights may be determined.
9. This procedure is continued until maximum stresses and displacements are found.

GRLWEAP Analysis Program

The research work carried out by Gobble (1998) and his co- workers led to the development of software named *GRLWEAP* for solving the problem of pile driveability analysis. *GRLWEAP* is the most realistic pile driving simulation software available. It makes estimating dynamic pile stresses, bearing capacities, blow counts and installation time a relatively simple task for the piling professionals.

Version 2005 of this software is more user-friendly, more accurate and faster than ever. It also includes new help features such as a continuously updated hammer database with over 650 hammer models and extensive driving system data.

The main features of the *GRLWEAP* Program (Version 2005) are given below.

- It predicts the driving resistance, dynamic pile stresses, and estimates the capacities of the pile based on field observed blow count for a given hammer and pile system.
- It replaces the blow count with speed of penetration for the analysis of vibratory driven piles.
- It helps in selecting an appropriate hammer and driving system for a job with known piling, soil and capacity requirements.
- It helps in determining whether a pile will be overstressed at a certain penetration or if refusal will occur before a desired pile penetration is reached.
- It is capable of estimating the total driving time.

Following are the highlights of *GRLWEAP*

- Expanded hammer data file
- Hammer data file continuously updated and internet accessible
- Expanded driving system data file
- Driving system data linked to hammer data
- Two different soil static analyses with simplified input

Analysis

In the present paper an attempt is made to study the effect of various parameters on the driveability for a given pile and soil profile, necessary in the pile driving analysis. A bearing graph analysis is carried out. The components involved in the study include soil, pile and hammer.

The various parameters to be considered for soil include shaft quake, toe quake, shaft damping and toe damping. The parameters to be considered are pile wall thickness, helmet weight and cushion stiffness.

The soil profile along with the properties is shown in Appendix I (*Courtesy: Institute of Engineering and Ocean Technology, Panvel, Maharashtra*). It involves two soils, viz., cohesive (clay) and cohesion less (sand). A circular pile of 1372 mm external diameter and 95 m long is considered in the present study and a hydraulic hammer of configuration MENCK MHU 1700. To study the effect of cushion stiffness on the pile driveability, another hammer of configuration MRBS 5000 is also considered. Cushion area for this hammer is 19,606 cm^2.

The values of different parameters considered in the present study are given in Table 1.

Table 1 Values of Various Parameters Considered in the Analysis (*After* Bowles, 1988)

Component	Parameter	Values
Soil	Shaft Quake (Q_s) [in mm]	1.6, 2.1 and 2.7
	Toe Quake (Q_t) [in mm]	3.5 and 7
	Shaft Damping (J_s) [in sec/m]	Clay:0.5, 0.7 and 0.8 Sand: 0.2 and 0.25
	Toe Damping (J_t) [in sec/m]	0.3, 0.6 and 0.8
Hammer (MENCK MHU 1700)	Helmet Weight (W) [in kN]	300, 330 and 390
Pile	Wall Thickness (t) [in mm]	40 and 42.5
Hammer (MRBS 5000)	Cushion thickness (t_c) [in mm]	250, 350 and 600

In order to study the effect of shaft quake (Qs) and toe quake (Q_t) a bearing graph analysis is carried out at the depth of 95 m and blow count is measured for specified soil resistance with shaft quake values and toe quake values as mentioned in Table 1. A similar procedure is adopted for studying the effect of shaft damping (Js) for cohesive and non-cohesive soils, the values to be varied being given in Table 1.

Further for studying the effect of toe damping, different values of toe damping as mentioned in the same table are considered with all other parameters being constant. For studying the effect of helmet weight (W), the pile hammer of the configuration MENCK MHU 1700 is chosen along with different values of the helmet weight. For the given pile, keeping all other values constant, only wall thickness (t) is varied as shown in Table 1.

In order to study the effect of cushion stiffness, hammer of the configuration MRBS 5000 is considered and cushion thickness is varied as indicated in Table 1. The effect of various parameters on the pile driveability is illustrated graphically in Figures 2-9.

Results and Discussions

From Figure 2 which illustrates the effect of shaft quake (Qs), it is observed that for a specified soil resistance of 32000 kN, the blow count increases from 357.8 to 518.1 blows/m for shaft quake values of 1.6 to 2.7 mm respectively. An increase in quake value by 0.5mm further increases the blow count by around 20%.

The effect of toe quake (Q_t) is shown in Figure 3. For a specified soil resistance of 29000 kN, blow count increases in the range of 236.2 - 267 blows/m for toe quake values of 3.5 and 7.0 mm respectively. This indicates an increase of around 13 % in the blow count for 3.5mm increase in toe quake value. The analysis reveals that shaft quake has more influence on driveability as compared to toe quake.

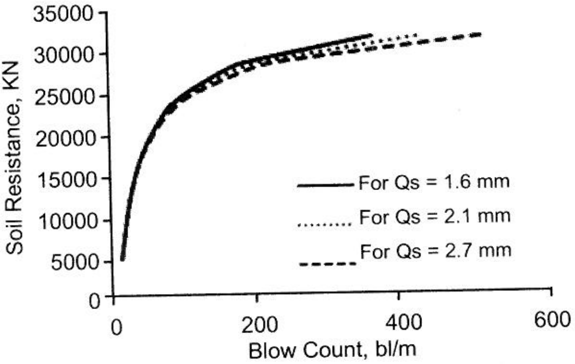

Fig. 2 Effect of Shaft Quake, (Qs)

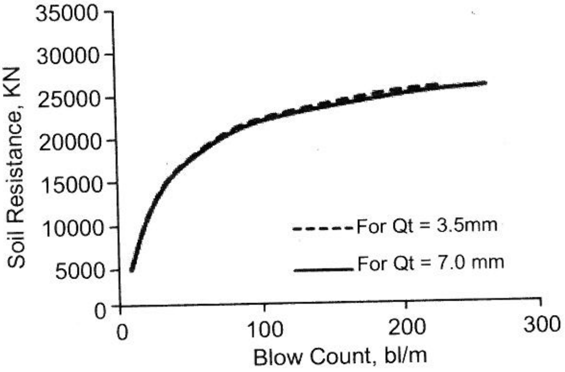

Fig. 3 Effect of Toe Quake (Q_t)

The effect of shaft damping (Js) is shown in Figure 4 for cohesive soil (clay) and Figure 5 for cohesion less soil (sand). In respect of cohesive soil, for a specified soil resistance of 29000 kN, the blow count values are observed to be 177.2, 259.3 and 357.3 blows/m for the damping values of 0.5, 0.7 and 0.8 sec/m respectively. This indicates an increase of around 32 % in blow count for 0.1 sec/m increase in the shaft damping values.

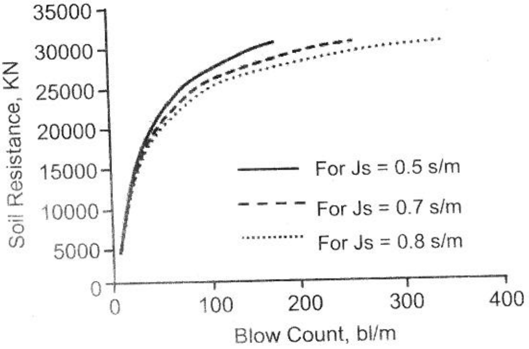

Fig. 4 Effect of Shaft Damping (Js s/m, Clays)

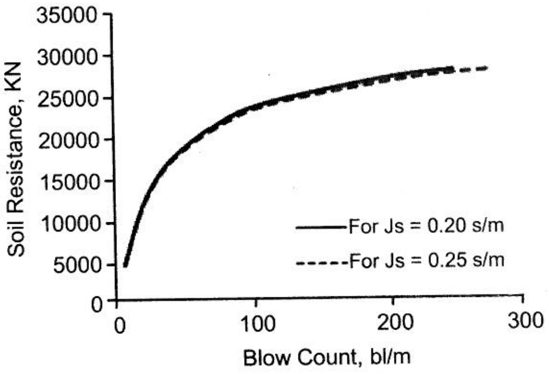

Fig. 5 Effect of Shaft Damping (Js s/m, Sands)

However, with respect to cohesion-less soils for a specified soil resistance, the blow count values are observed to be 248.7 and 277.6 blows/m for the damping values of 0.2 and 0.25 sec/m respectively. For 0.05 sec/ m increment in damping values, increase in blow count is observed to be 11%. This shows that, shaft damping has more influence in case of cohesive soil than in cohesion-less soil.

Figure 6 shows the effect of toe damping (J_t). When the toe damping values are increased from 0.3 to 0.8 sec/m for a specified soil resistance, the blow count values also increase from 197.2 to 235.2 blows/m respectively. Around 10 % increase is observed in blow count for every 0.1 sec /m increment in shaft damping values. This shows that the effect of toe damping is much less as compared to shaft damping.

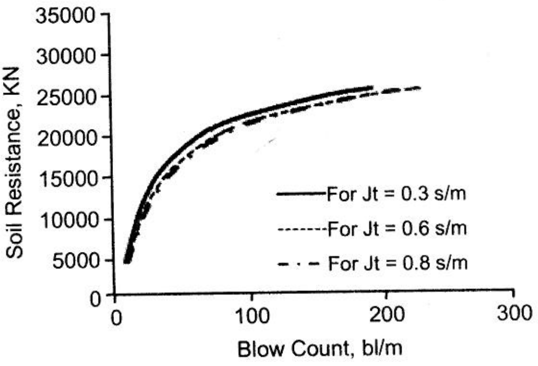

Fig. 6 Effect of Toe Damping (J_t, s/m)

The effect of helmet weight is shown in Figure 7. For a specified soil resistance of 32000 kN, the blow count values are observed to be 274.5, 338.7 and 357.8 blows/m, respectively corresponding to the helmet weights of 300, 330 and 390 kN. An increase of 18% in blow count for 30 kN increase in helmet weight is observed.

The effect of helmet weight is shown in Figure 7. For a specified soil resistance of 32000 kN, the blow count values are observed to be 274.5, 338.7 and 357.8 blows/m, respectively corresponding to the helmet weights of 300, 330 and 390 kN. An increase of 18% in blow count for 30 kN increase in helmet weight is observed.

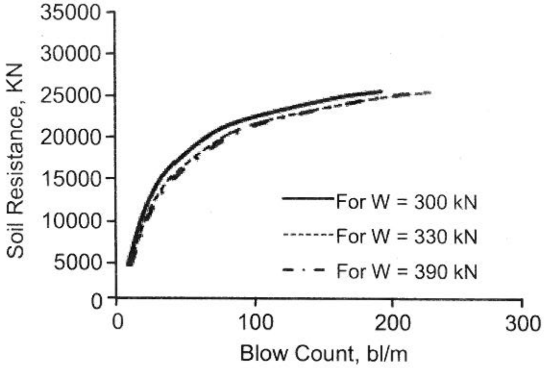

Fig. 7 Effect of Helmet Weight (W, KN)

The effect of pile wall thickness, t is shown in Figure 8. For a specified soil resistance of 32000 kN, the blow count values are observed to be 161.4 blows/m and 262.7 blows/m corresponding to wall thicknesses of 4.25 mm and 4.0 mm respectively. Thus, an increase in blow count to the tune of around 55% is observed for an increase of 0.25mm in wall thickness of the pile. This shows that the effect of pile wall thickness on driveability of the pile is more predominant as compared to all other parameters.

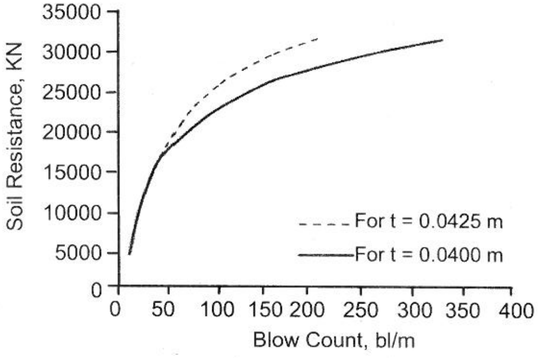

Fig. 8 Effect of Wall Thickness (t, m)

Figure 9 illustrates the effect of cushion stiffness on pile driveability. The blow count values obtained corresponding to 250, 350 and 600 mm cushion thickness values are 253.7, 248.6 to 244.6 blows/m respectively. An increase of around 3 % is observed in the blow count for 100 mm increase in cushion thickness. Thus, the analysis shows that, there is a lesser effect of cushion stiffness on driveability.

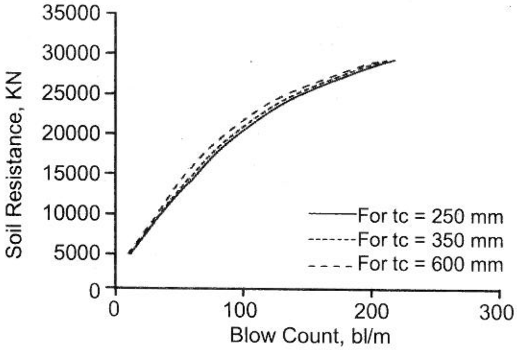

Fig 9 Effect of Cushion Stiffness, t_c

Summary and Conclusions

Pile driveability analysis based on the basic concept of wave equation analysis of piles is reported in the present paper. The analysis is carried out using a program package GRLWEAP. The effect of various parameters on the pile driveability is examined in the analysis. The following conclusions are reached.

- Shaft quake has more influence on pile driveability as compared to toe quake.
- Shaft damping has more influence in cohesive soil than that in a cohesion-less soil.
- Effect of toe damping is considerably less as compared to shaft damping.
- The effect of helmet weight is quite appreciable on the pile driveability.
- Effect of pile wall thickness is more predominant as compared to other parameters.
- Effect of cushion stiffness is very less on the pile driveability.

Appendix – 1 Soil Profile and Design Parameters (IEOT, ONGC Panvel)

Layer No:	Depth	Soil type	Plasticity	Density	ϕ	S_u	Eff. Unit weight	f_{lim}	q_{lim}	ε_{50}	k
	m				deg	kPa	kN/m^3	kPa	Mpa	%	MN/m^3
1	0.0-3.2	Silt			25		8.5	20	3		5.5
2	3.2-5.2	Sand		d	35		9.0	20	5		34.6
3	5.2-7.0	Sand		d	30		9.5	20	3		16.6
4	7.0-9.0	Sand		m	25		9.0	60	5		5.5
5	9.0 -10.0	Silt			25		9.0	20	3		5.5
6	10.0 -13.0	Clay	lp-mp				7.5			1.0	
7	13.0-14.5	Silt			25		9.0	20	3	1.5	5.5
8	14.5 -24.0	Clay	lp-mp				7.5			1.5	
9	24.0-28.0	Clay	hp			70	9.0			1.0	
10	28.0-29.0	Sand			30		9.5	20	6		16.6
11	29.0 -45.0	Clay	hp				8.5			1.0	
12	45.0 -48.0	Sand		d	35		10.0	20	6		34.6
13	48.0 -50.0	Clay	hp			110	9.5			0.5	
14	50.0-54.0	Sand		d	35		10	20	6		34.6
15	54.0-65.0	Clay	hp			150	9.0			0.5	
16	65.0-69.0	Silt			25		8.5	20	3		5.5
17	69.0-79.0	Clay	hp			180	9.0			0.5	
18	79.0-83.0	Sand			30		9.0	20	6		16.6
19	83.0-86.0	Clay				200	10.0			0.5	
20	86.0-94.0	Sand		d	35		9.5	50	5		34.6
21	94.0-99.0	Sand			35		10.0	20	7		34.6
22	99.0-104.0	Sand		d	30		9.5	20	4		16.6
23	104.0-109.0	Sand			30		9.5	20	4		16.6
24	109.0-111.0	Clay	hp			225	9.5			0.5	
25	111.0-115.0	Sand			30		9.5	20	4		16.6
26	115.0-123.0	Clay				250	10.0			0.5	

Note :

Plasticity = lp/mp/hp : low /medium/ high plasticity

ε_{50} = strain at 50% failure stress

Density = l / m / d : loose / medium / dense sand

q_{lim} = limit unit end bearing pressure

f_{lim} = limit unit skin friction,

k = Coefficient of variation of modulus of subgrade reaction

S_u = Cohesion

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