Pile dynamic versus static load tests in fine-grained deposits of Southwest Iran with special attention on soil setup effects

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ABSTRACT

Many precast driven piles have been constructed in soft soils of southwest Iran in Khuzestan Province in oil, gas, petrochemical and other industrial projects within the past 20 years. Estimating the adequate pile bearing capacity and drivable embedment depth of piles are always a major challenging task both during the design and construction phases. Clients have been promoted to carry out dynamic load test (DLT) and static load test (SLT) on both "test piles" and "construction piles" to optimize the pile design and improve the execution quality. Data sets of several projects with number of piles ranging from 5000 to 8000 in each project are compiled for comparison purposes of the ultimate load obtained from DLT with SLT tests. The study area geological stratification is mostly comprised of soft cohesive layers on top underlain with medium stiff to stiff strata. Soil setup potential is understood to be considerable in the region. During the pile testing program, it has been attempted to carry out DLT at the end of drive as well as restrike at different time intervals up until few weeks or months. Then correlations for soil setup are used to determine the parameters of the study site such as "A" and t0 of Skov and Denvor relation. The results have shown that the t0 is very variable in the region ranging from 0.1 day in highly permeable strata up to 1 day in pure cohesive strata with low permeability. The results also indicate that if the DLT tests are corrected for setup effects equivalent to the SLT time past from the initial drive, more accurate agreements could reach. During piling operation, as it may not be feasible to wait for sufficiently long time for the setup to occur, and usually DLT tests are carried out within few days from pile installation, the extrapolated capacities considering site specific setup effects are used in verifying the design capacities. Considerable savings are made through the explained procedure both in "construction cost" and "construction time" of the projects.

Keywords: precast driven pile, soft soil, setup, dynamic load test, static load test

1 INTRODUCTION

Driven pile foundations are used to transfer the superstructure loads to the ground deep enough in order to increase capacity and prevent excessive settlements. Estimation of axial capacity plays an important role in foundation design. The prediction of pile bearing capacity can be achieved using different methods such as static analysis, direct methods based on in situ tests (SPT, CPT, …) as well as static and dynamic load tests (Fakharian and Khanmohammadi, 2015). One of the important issues in precast driven piles is variation of bearing capacity over time after the initial drive. It is well known that driven piles in clayey deposits typically undergo a time-dependent increase in capacity following initial installation due to “soil setup” (Svinkin, 1996) (Bullock *et al.*, 2005). The static and the dynamic pile load testing methods are the two main tests periodically carried out to assess the pile load capacity and setup measurement.

Owing to increasing time and cost, particularly with the difficulties associated with transporting static load testing accessories into congested city centres, the lack of space on many sites, heavy and time-consuming test arrangements requiring surcharge or reaction piles in top-down tests, alternatives for pile testing have been adopted. The tendency of clients and contractors has been employing dynamic techniques in order to supplement ordinary static load tests. Dynamic load testing (DLT), also known as High Strain Dynamic Testing (HSDT) was introduced in Iran in the late 90s and eventually has become popular since then (Fakharian, 2000; Fakharian and Attar, 2010; Sarrafzadeh *et al*., 2012; Fakharian *et al.*, 2013; Asghari Pari *et al.*, 2019, 2020). The dynamic load tests are faster and more convenient than SLT at times and also offer significant cost savings. Although there are several other advantages in conducting dynamic pile testing such as integrity evaluation, hammer delivered energy, etc., obtaining the pile ultimate load is normally the main objective of the test. The ability to accurately predict static load capacity from dynamic pile testing has been discussed in many studies before. Likins and Rausche, 2004 have reported that the pile capacity tested using HSDT correlated well with the static load test results. Gue and Chen, 1998 showed that HSDT over-predicts the pile capacity by more than 60%. They commented that HSDT could only be an effective means of construction control. Sarrafzadeh *et al*., 2012 and Fakharian *et al*., 2013, and Hosseinzadeh Attar and Fakharian, 2013 compared SLT and DLT results through considering the soil setup effect for a construction site. They concluded that compensating the time differences of performing SLTs and HSDTs is an important issue in the analysis and interpretations of DLT results. On the basis of the extensive data collected within the past two decades from piling projects in southwest Iran, attempts are made to further manipulate the correlations between DLT and SLT tests herein.

This study is aimed to compare the predictions of the pile Dynamic Load Tests (DLT) with Static Load Tests (SLT). Two queries and their answers serve as a prime objective to this paper: (i) Do SLT and DLT always produce comparable ultimate loads? (ii) Does DLT truly simulate static load-displacement behaviour of a pile? For this purpose, this paper presents case histories of the high strain dynamic load tests and static load tests carried out at five large piling projects on piles embedded in dominantly clayey deposits based on well documented test results.

2 CASE HISTORIES

In order to illustrate the application of DLT and its comparison with SLT results, the following five case studies are selected and interpretations are made on the test results.

2.1 Case 1: Arvand Jahan Ara Steel

Arvand Jahan Ara Steel (AJS) Making Plant area is located near Khoramshahr city in Khuzestan province. The underlying subsoil generally consist of clayey layers with alternates of silt and sand. A detailed field testing program was planned for the 400×400 mm precast square driven piles including DLT testing (using PDA), signal matching analysis (using CAPWAP), and SLT testing. The pile embedment depths are in the range of 15.7 m to 22 m. All piles were driven and tested both at "End Of Initial Drive" (EOID) and “Beginning of Restrike” (BOR) condition uisng PDA equipment. SLTs were performed on four piles D-TP1 through D-TP4.

The pile installation records of the four test piles shown in Fig. 1 indicate consistency between the blow count profile and SPT’N and CPTu profile of the adjacent boreholes.

2.2 Case 2: BIDBOLAND II Gas Refinery

BIDBOLAND II Gas Refinery project is located near Mahshahr city in Khuzestan province. Soil layers in the study area generally consist of clayey soils. A detailed field testing program was planned for the pre-stressed close-end spun concrete piles having circular outer diameters of 450 and 600 mm including DLT, CAPWAP and SLT. The "Pile Testing Program" on 28 "Test Piles" across the project site was carried out from February 24, 2016 through March 30, 2016. The pile embedment depths are in the range of 21.4 to 33.2 m. All piles were tested both at EOID and BOR condition. SLTs were performed on three piles C3A-TP5, C4A-TP5 and C5A-TP5. The pile installation records shown in Fig. 2 indicate good agreement in the driving resistance of the test piles to soil consistency of the respective adjacent boreholes.

2.3 Case 3: North Azadegan Oilfield

The North Azadegan Oilfield is approximately located 80 km west of Ahwaz city and southwest of Susangerd. The Azadegan Oilfield extends North-South, with an apparent length of 60 km and width of 20 km. Soil layers in the study area generally consist of clayey layers. In order to determine the pile bearing capacity and to optimize the required pile embedment depths, 14 “Test Piles” were driven at different points of 60-Hectar central processing facilities (CPF) site. All the piles were 400 mm square precast concrete, comprised of two segments spliced by 4 bolts. DLTs were carried out on all test piles at EOD and BOR conditions. The DLT program was performed in three time phases in order to

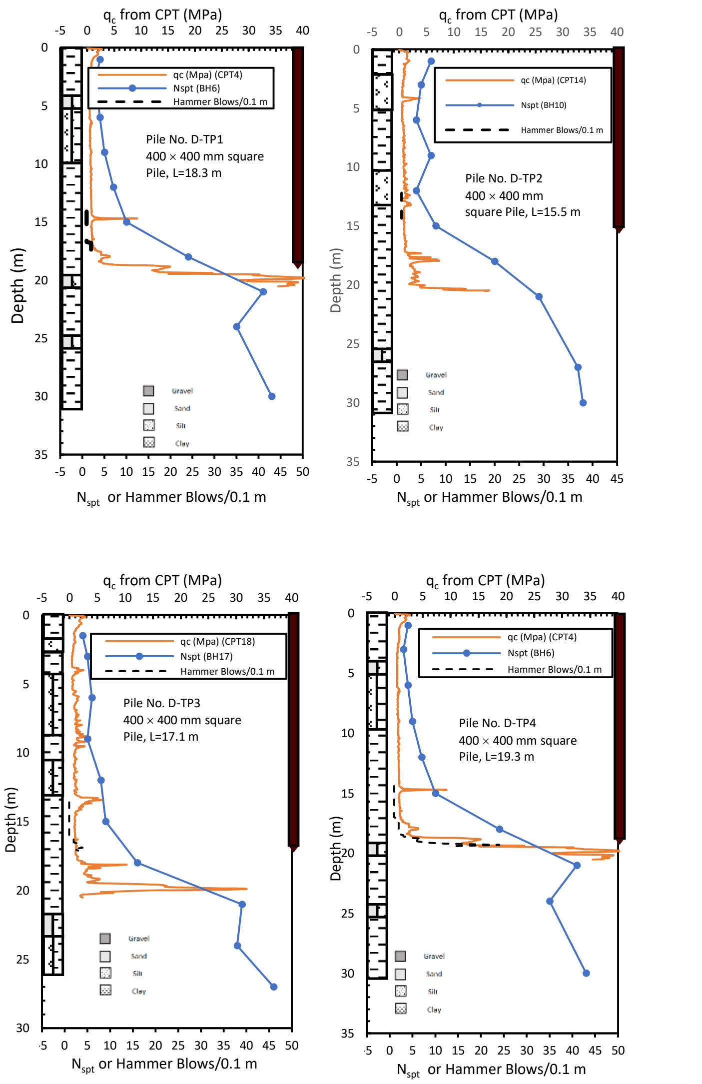

Fig. 1. SPT'N and CPTu profile with pile installation records (Case 1)

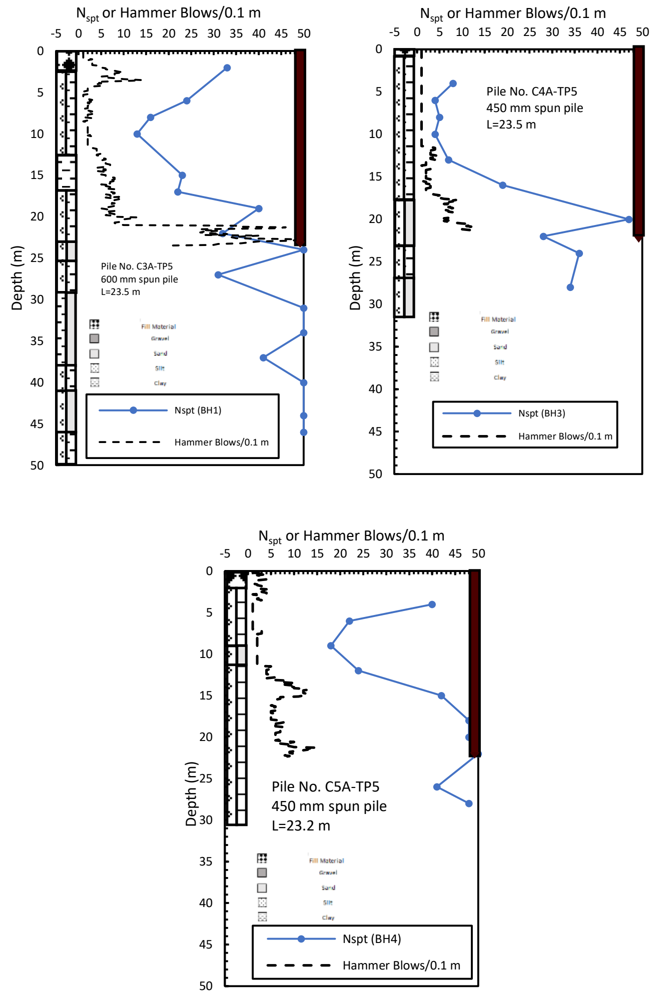

Fig. 2. SPT'N profile with pile installation records (Case 2)

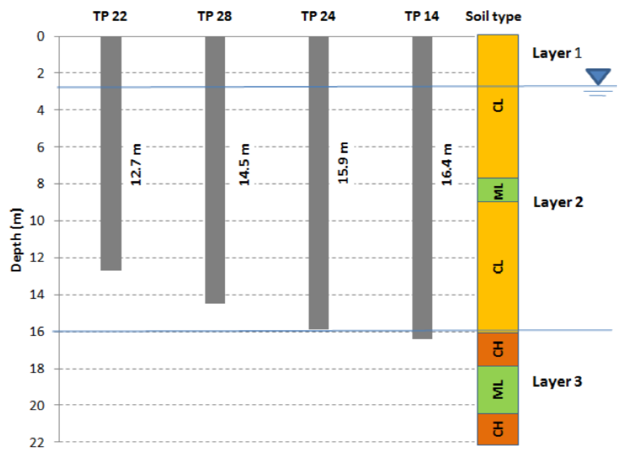

Fig. 3. Test Pile lengths with respect to the soil layers (Case 3)

verify the variations in the pile capacities over time. The first phase of the DLTs were carried out at the same time of driving the test piles (EOD). The second phase of tests was performed within 1 to 3 days after initial driving of piles. In the third phase, the BOR tests were repeated in 14 days after initial driving of piles. Out of the 14 "test piles" in the study site, SLT was carried out on 4 test piles TP14, TP24, TP28 and TP22. The pile lengths with respect to the soil layers are shown in Fig. 3.

2.4 Case 4: Fajr II Utility Plant

Fajr II is a 32-hectar utility plant in PetZone of Mahshahr. The site accommodates a power plant, pre-treatment and treatment water units and air unit. The dominant soil layering across the construction site is a very soft to stiff clay, average of 15 m thick, overlain a medium dense to dense sand, 4 to 8 m thick (that the pile tips are mostly embedded within this sandy layer), continued by a stiff to very stiff clay, 3 to 5 m thick, overlain a dense to very dense sand, 4 to 8 m thick, continued by a stiff to hard clay. Different types of precast and prestressed driven concrete piles at 8700 points with a total length of 150,000 m have been constructed. About 7000 points of the piles include 450 mm outside diameter prestressed spun piles with wall thickness of 80 mm and closed-toe. The spun piles have been driven to embedment depths ranging from 14 through 22 m. Static load tests were carried out on 33 piles. 462 piles were monitored by 566 DLTs. Out of 462 piles DLT tested, 82 piles were monitored during continuous driving only (EOD), 282 piles were tested at restrike (one time or more) and 98 piles were tested both during continuous driving and at restrike (one time or more).

2.5 Case 5: South Azadegan Oilfield

The South Azadegan Oilfield is approximately located 80 km west of Ahwaz city, southwest of Susangerd, and south of North Azadegan. Soil layers in the study area generally consist of clayey layers. In order to determine the pile bearing capacity and to optimize the required pile embedment depths, 40 “Test Piles” were driven across site. All the piles were 400 mm square precast concrete, comprised of two segments spliced by 4 bolts. Dynamic load tests (DLT) were carried out on all test piles at EOD and BOR. Out of the 40 “test piles”, SLT was carried out on 7 test piles.

3 RESULTS AND INTERPRETATIONS

Extensive DLT and SLT tests were performed under adequate supervision and employing calibrated hydraulic jacks and measurement devices such as load cells and displacement measurement transducers. Figure 4 presents sample views of DLT and SLT test setups. Representative DLT and SLT results are presented in Figs. 5 and 6 showing the comparison between load-displacement plots for the cases 1 and 2, respectively. Results of Fig. 5 are attributed to four different test piles (TP1 to TP4) unto which DLT at EOD and restrike has been carried out (BOR) after 13, 12, 11 and 2 days, respectively. The mentioned test piles are having embedment depths of, respectively, 18.3, 15.5, 17.1 and 19.3 m. The corresponding SLT tests were carried out after 14, 30, 22 and 9 days from EOD. It is noticed that the ultimate load obtained from both DLT (at BOR) and SLT results are considerably greater than the EOD magnitudes.

Similarly, the load-movement plots obtained from DLT and SLT results of Case 2 are plotted in Fig. 6. The test piles C3A-TP5, C4A-TP5 and C5A-TP5 are having embedment depths of 23.5, 23.5 and 23.2 m, respectively. The DLT tests at restrike were performed after 13, 27 and 20 days and SLTs after 43, 60 and 42 days from EOD, respectively, for the mentioned test piles. It is noticed that both DLT at BOR and SLT ultimate loads are considerably greater than EOD. Other than pile ultimate load, the stiffness responses have also increased over time.

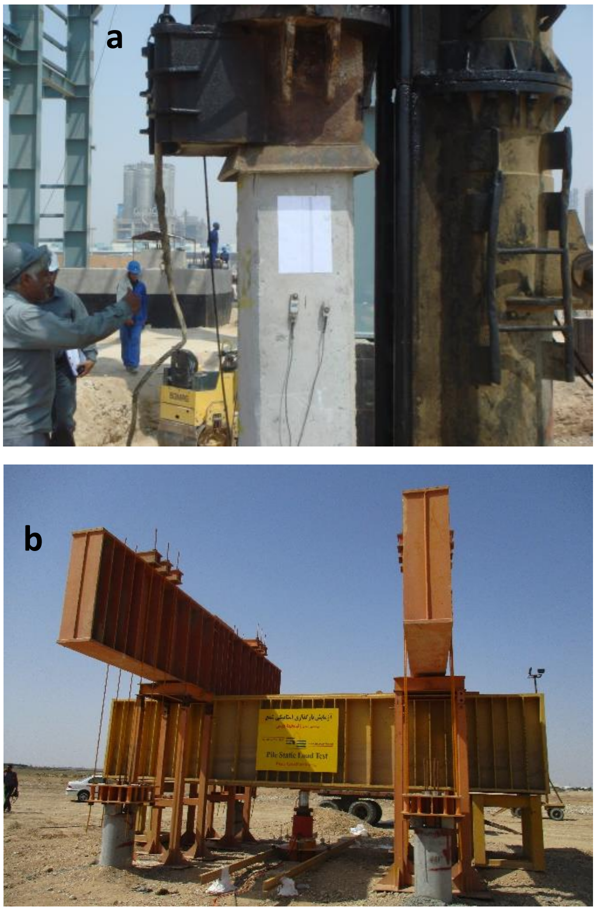

Fig. 4. Typical pile testing plans: (a) Dynamic load test, (b) Platform, girders and reaction set up for static axial load tests.

The increases in pile capacity are attributed to a well-known phenomenon referred as soil setup. Soil setup is the result of generation of excess pore water pressure during the pile installation and subsequent dissipation over time after the pile initial drive, causing the soil surrounding the pile to consolidate and hence increase the soil strength and stiffness. One major question in engineering practice is how well the DLT and SLT tests compare to each other? As a matter of fact, the pile capacity increases over time. The rate of increase is significant at the early times (up to a reference time t_0), beyond which the increase rate becomes linear in log time scale, as has been reported in literature (e.g., Svinkin, 1996, Chow *et al.*, 1997, Axelsson, 2000, Bullock *et al.*, 2005, Fakharian and Khanmohammadi 2022). The increases in pile capacities might become insignificant after certain times, from couple of days up to several months, depending on soil permeability and drainage conditions. Therefore, for a meaningful comparison of the pile test results, it is necessary to notice the time of testing from EOD.

Figure 7 shows the comparison of interpreted pile capacity of the aforementioned test piles of the five cases from DLT and SLT results.

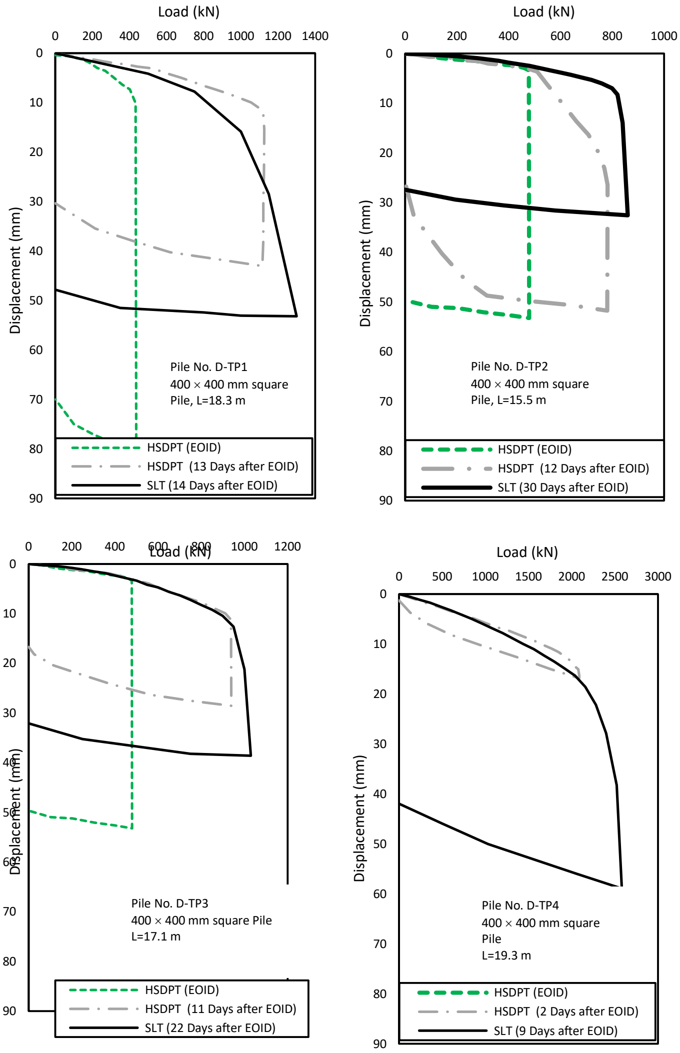

Fig. 5. Load movement response of test piles from DLT and SLT tests at EOD and up to 30 days from EOD (Case 1)

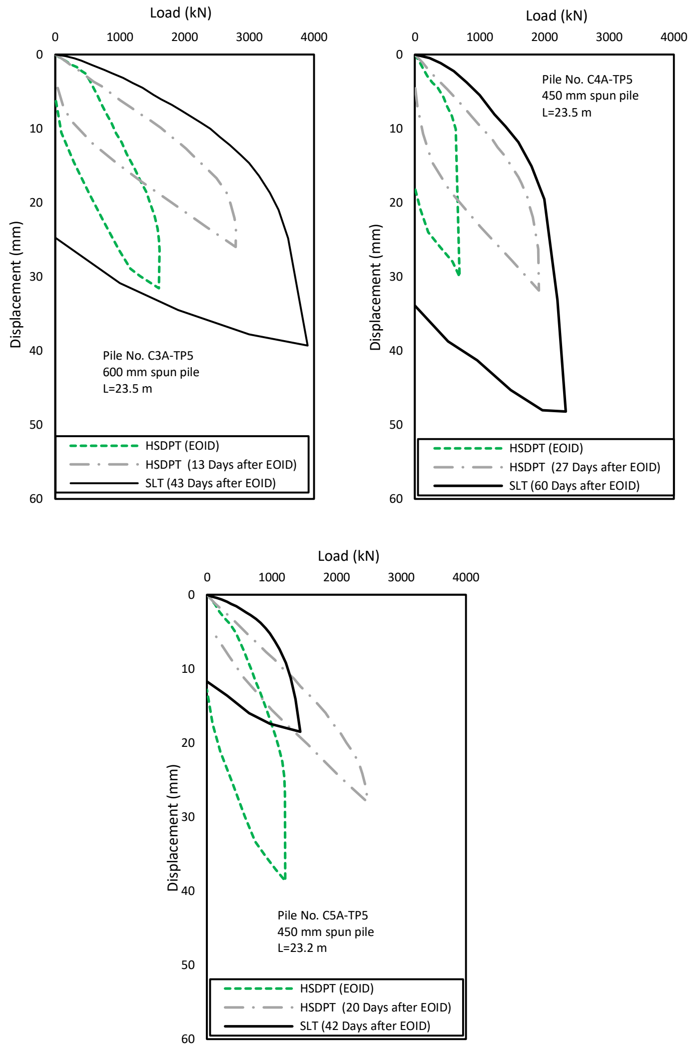

Fig. 6. Load movement response of test piles from DLT and SLT tests at EOD and up to 30 days from EOD (Case 2)

Davisson offset limit method is used to determine the ultimate capacity of SLTs. Also Signal matching analysis using CAPWAP is used to obtain total ultimate capacity and distinguish the tip and shaft resistances of DLTs. The results from both methods seem to be in reasonably fair agreement with each other. It is noticed, however, that in most cases the ultimate capacity obtained from SLT are greater than the DLT results. The main reason of underestimating the capacity in DLT results is differences and variabilities in the testing time. Most SLTs were performed after a longer time compared to DLT. At the time of PDA tests, soil setup effects were not been completed yet. It is also understood that the main portion of the soil setup occurs in the pile skin frictional resistance. The tip resistance is less affected by the soil setup. Therefore, the focus here is on the skin frictional resistance component.

To compensate for the differences of the test times, the skin friction is obtained through signal matching analysis of the DLT test results. Then the empirical relation proposed by Skov and Denver, 1988 is used at each site and the parameters are back-calculated through the trend of setup at each site for the skin friction. In this relation, the effect of soil set-up is considered to be a function of time logarithm as shown in Equation 1.

$$Qt/Q0 = 1 + A\,[\log(t/t0)] \qquad (1)$$

where Q_t is pile ultimate load at time t (shaft load in this study), Q_0 is the pile ultimate load at time t_0, A is a factor dependent on soil type, and t_0 is a reference time. It should be noted that t_0 is a function of soil type and pile geometry. Using prestressed concrete piles and H-piles, Camp and Parmar, 1999 empirically determined the reference time equivalent to 2 days, but stated that t_0 equal to 1 day seems to be more reasonable. Svinkin and Teferra, 1994 proposed t_0 equal to 1 to 2 days. Bullock, 1999 recommend standardizing the reference time to 1 day.

The setup factor A is also back-calculated from DLT results at different times from EOD. Having used signal

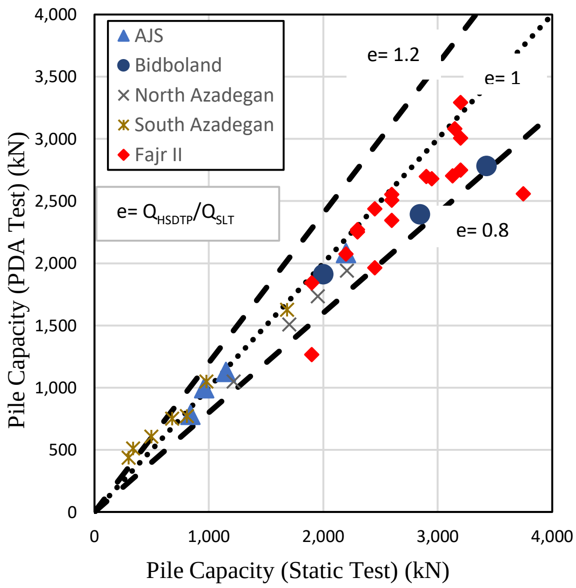

Fig. 7. Comparison of static (SLT) and dynamic (DLT) load test results

matching analysis, the tip and skin frictional resistances are distinguished first. Then Qs,t/Qs,t₀ for corresponding t/t₀ is calculated for each pile, out of which A has been determined using Skov and Denvor correlation.

The variations of normalized skin resistance (Qs,t/Qs,t0) with respect to log(t/t0) for D-TP3 (Case1) and C5A-TP5 (Case2) are plotted in Fig. 8.

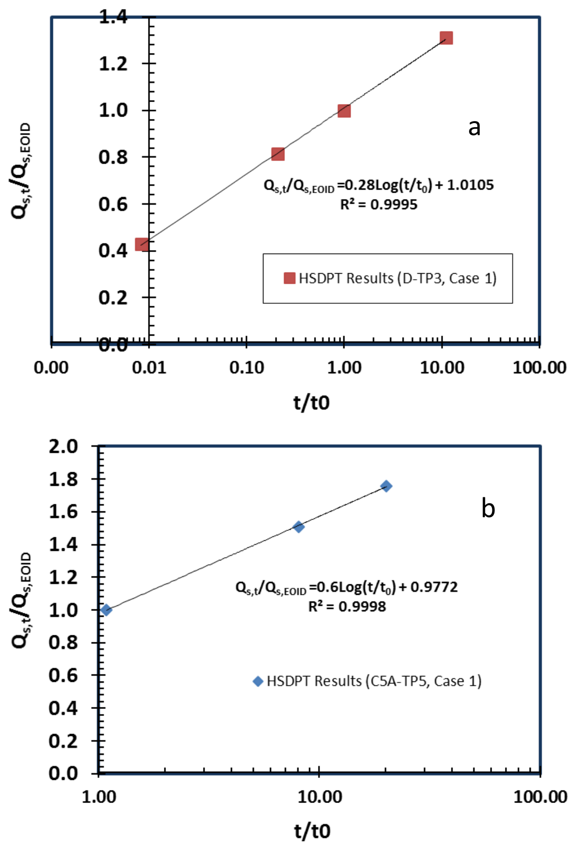

Fig. 8. Variations of normalized skin frictional resistance with log time to obtain parameter *A*: (a) Case 1, (b) Case 2

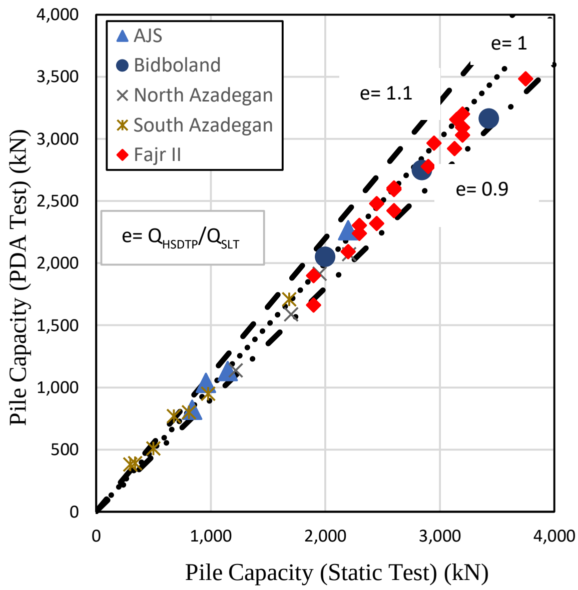

Fig. 9. Comparison of DLT and SLT when modifications on soil setup effects are performed

The setup factors are obtained equivalent to 0.28 and 0.6 fir cases 1 and 2, respectively. The same factor for all the five cases are determined and summarized in Table 1. It is noticed that t_0 is obtained as 0.1 day in Case 4 and the best estimates have been unity for rest of the cases. The A parameter has been obtained as low as 0.28 in Case 1 and as high as 0.6 in case 2. Higher A values correspond to higher setup potential of the specific site. The reason for lower t0 magnitude at Case 4 is the existence of many randomly distributed sand sublayers, lenses and seams enabling rapid dissipation of excess PWP and hence faster stabilization of the setup rate. The magnitude of A value depends on a number of parameters including soil plasticity index, permeability, over-consolidation ratio thickness of compressible strata, etc. More detailed evaluations of required at each study site to find out correlations between the two parameters with the site stratification and other factors such as pile geometry. For example, more details are presented on setup potential of Case 2 and its correlations with OCR and pile geometry in another publication in this proceedings (Behroozian and Fakharian, 2022).

Table 1. Soil setup parameters for all the five cases

Case ID	t_0 (day)	A
Case 1	1.0	0.28
Case 2	1.0	0.60
Case 3	1.0	0.50
Case 4	0.01	0.30
Case 5	1.0	0.42

Skin frictional resistance for the time difference between DLT and SLT tests was calculated using the setup parameters of each case study and added to DLT predictions. The corrected capacity is referred to as "modified dynamic test". The modified results are presented in Fig. 8. A much better correlation is observed between SLT and DLT test results after having compensated for the time differences and modifications to the pile ultimate loads.

4 CONCLUDING REMARKS

Dynamic load test is commonly carried out as an alternative to ordinary static load test owing to high costs and time-consuming tasks of SLT. Moreover, pile integrity assessment is an additional advantage of the dynamic load test. DLT is gaining increasing popularity and is being used extensively to estimate the pile capacities and integrity in Iran in the past 20 years. It has then become necessary to evaluate and improve its productivity to make comparable predictions to that of SLTs. However, reliable long-term prediction of DLTs may not be straight forward and involves many complex issues including testing the same pile twice or even several times, testing adjacent piles, time effects, errors associated with testing, expertise of the test engineers, etc. Therefore, establishing setup correlations to adequately extrapolate the pile ultimate loads measured by DLT at sufficiently long time is necessary. For this purpose, at each construction site, it is necessary to plan pile DLT on several pile lengths and at different times from EOD. Then conducting SLT at a time ranges of 40 to 60 days. On the basis of the extensive pile test data, site specific setup parameters like A and t_0 should be established on the basis of which evaluation of ultimate pile capacity could be reliably predicted through conducting short-term restrike tests such as 1 to several days, in order to expedite the confirmation process of the approvals. This would have ended up in time management of QC/QA while the cost management of the project is also satisfied through proposing optimized capacities and lower factor of safety due to having performed sufficient test piles both during the “test pile” study and installation of the “working piles”.

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