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Assessment of ultimate load of drilled shaft socketed in rocks based on pile load tests

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Abstract. To investigate the settlement characteristics of drilled shaft socketed into igneous, metamorphic, or sedimentary rock, experimental results of the pile load tests were thoroughly collected in 20 different locations, clearly tabulated, and extensively compared with the standards for assessment of ultimate load. Total and elastic settlement patterns of drill shaft were completely dependent on the socketed pile length, the imposed load, the pile diameter, and the shear stress in bedrock, whereas residual settlement did not depend on the factors. It was also observed that the trends of total, residual, and elastic settlements were independent on bedrock types. Comparison between the experimental data and the standards shows that the total and residual settlements of large drilled shaft socketed in bedrock were too high to determine the ultimate load, and the reasonable amount of total or residual settlement measured from pile load test is proposed to assess the ultimate load capacity of drilled shaft socketed in bedrock.

Keywords: bedrock; drilled shaft; pile load test; residual and total settlement; ultimate load capacity

1. Introduction

With the growth of cities, there has been rising demand for constructing ultra high-rise buildings, industrial facilities, and infrastructures in or near urban areas, e.g., skyscraper, nuclear power plants, chemical facilities, ultra-long span bridges, international hub airport, and mammoth scale of industrial port. For appropriate performance of these structures, the large loads induced by these structures are completely transferred to substructures, i.e., foundations. A drilled shaft, which is also called caisson and used as a high-capacity cast-in-place pile, is one of the best solutions effectively and safely to transfer such a large imposed load to the bearing layers.

If the bearing capacity of the drilled shaft is not enough, the drilled shaft can be significantly damaged and excessive settlement occurs, resulting in the failure or collapse of superstructures and facilities. Therefore, extensive studies on load transfer mechanism and prediction models for drilled shaft have conducted in the past four decades. According to the Canadian Geotechnical Society (2006), the structural loads can be transferred to the bearing layer via side shear, end bearing, or both side shear and end bearing. In 1976, Rosenberg and Journeaux first reported the empirical relationship between unconfined compressive strength of rock and the side shear. A design method for single sockets based on side resistance of rock sockets in sandstone, mudstone, and shale was developed by Williams and Pells (1981). Rowe and Armitage (1987) proposed the design method for drilled piers in soft rock and the model also predicted the bearing capacity of drilled shafts. McVay *et al.* (1992) developed a design guideline for drilled shafts socketed in limestone based on the fact that the skin friction was a dominant factor. Dimensional analysis of drilled shaft side resistance in sand was conducted by Turner and Kulhawy (1994). In 1998, Zhang and Einstein proposed an analytical relationship between the unconfined compressive strength of intact rock and the end bearing capacity of drilled shafts socketed into rock. Rollins *et al.* (2005) developed load-displacement curves for skin friction of drilled shaft in gravelly soils from uplift load tests. Mullins *et al.* (2006) developed design procedures to determine the unit end bearing capacity of post-grouted drilled shaft in cohesionless soils. In 2010, Shahin used artificial intelligence techniques, called artificial neural network, to develop the models that predict the axial capacity for drilled shafts. Chen *et al.* (2010) investigated the lateral criteria to evaluate the capacity of rigid drilled shaft under the lateral loading. Zhang (2010) proposed an empirical model to predict the end bearing capacity of rock-socketed drilled shaft based on rock quality designation. Chen and Chu (2011) examined the uplift interpretation criteria for the drilled shafts subject to axial loading in gravelly soils. In 2015, Ng and Myers performed the numerical analysis to develop the procedures for drilled shaft socketed in granular soils and the discrete element method was employed to investigate various input parameters. Thiyyakkandi *et al.* (2016) investigated the coupled torsion and lateral behavior

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of mast arm drilled shaft. In 2017, Jeong *et al.* conducted numerical analysis for the drilled shaft installed in weathered soils subjected to lateral cyclic loading and proposed the cyclic p-y curves to capture the behaviors of the drilled shaft. Khanmohammadi and Fakharian (2018) carried out numerical simulations using ABAQUS for piled-raft foundations in order to determine the optimal combination of pile length and spaces between piles. Ko *et al.* (2018) conducted 3D numerical analysis to develop the optimal design of piled raft foundation. In 2019, Fenu *et al.* proposed the simple method to obtain the optimal shape and length of pile subjected to lateral loads based on finite element analysis. Hsiao *et al.* (2020) used rock quality designation to determine the side resistance of drilled shaft installed in bedrocks. Pile load tests for long rock-socked piles were performed by Zhang *et al.* (2020) and the vertical bearing characteristics and the design guideline for anchor piles were provided. In spite of the numerous published studies, there is no research available for the determination of the ultimate load capacity of the drilled shaft socketed into rock based on the load-settlement measured from the pile load test. In general, after installing the large drilled shaft in field, the pile load tests are necessary to evaluate and investigate the response of drilled shaft and its safety. Through the extensive literature review, it was found that the standards were existed for determining the ultimate axial load capacity of driven pile based on the total or residual settlement from the pile load tests. However, these criteria were not suitable to the rock-socketed drilled shaft. Thus, there is a fundamental need for comprehensively comparing the field data with the standards to propose new criteria.

The remainder of this paper is organized as follows. First, the standards, which have been published and proposed by many researchers and organizations, are extensively summarized and systematically tabulated. Second, the collected results from pile load tests are analyzed and investigated in terms of total, residual, and elastic settlements. Subsequently, the experimental data are comprehensively compared with the standards, and eventually the new criterion is proposed in order to determine the ultimate load capacity of drilled shaft socketed in rocks based on the total or residual settlement measured from the pile load tests.

2. Previous studies on assessment of ultimate load capacity

2.1 Determination of ultimate load based on total settlement

Although the ultimate limit state can be defined as the state in which the settlement infinitely occurs without additional increment of load, it is impossible to identify such an ideal ultimate load capacity of the drilled shaft socketed in rock under the ultimate limit state by the pile load test in practice. Therefore, it is widely used in practice that the load can be defined as the ultimate load at the moment when a total or residual settlement reaches a certain amount or less. This signifies that the structures are designed to allow a small amount of settlement and then it is possible for the pile foundation to settle within the allowable amount. However, since the settlement can exceed the allowable settlement, the allowable load capacity is determined by using a factor of safety.

Based on comprehensive literature review (EM 1110-2-2906 1991, Seo and Yoon 2004, Kim 2013, Hong *et al.* 2016), it was found that the standards for the amount of total settlement with respect to the ultimate load vary according to the organizations and researchers, as summarized in Table 1 In India (IS 2911 2010), the ultimate load was calculated when the total settlement of 12 mm was reached. Germany, France, Belgium, and Muns (1959)'s standard was the total settlement of 20 mm. Terzaghi and Peck (1967), Touma and Reese (1974), Austria, Holland, and New York City code suggested that the ultimate load was determined at the total settlement of 25.4 mm as measured in the test. According to Roscoe (1957), the British Standard (BS 8004 1986), the Japanese Standard (JGS 2007), and Tomlinson and Woodward (2014), for pile with a diameter of up to 1 m, the ultimate load as estimated by pile load tests was calculated at the moment when the total settlement was equal to a 10% of the pile diameter. Since it was considered that the total settlement depends on the type of piles, De Beer (1964) proposed that failure loads for a driven pile and cast-in-place pile were determined from the loads as the pile head settled down to 10 and 30% of the pile diameter, respectively. In research conducted by Van Impe (1988), the settlement, equal to 5% of the pile diameter, was used to calculate the ultimate load. In addition to the above standards based on the total settlement or a ratio of the total settlement to the pile diameter, the incremental settlement per unit load was employed to determine the ultimate load. The standard of California, Chicago, Ohio, and the Raymond International was total incremental settlement per unit load of 0.254, 0.762, and 1.27 mm/tonf, respectively.

2.2 Assessment of ultimate load capacity using residual settlement

In general, for the long pile and under the condition of large applied load, an elastic deformation of the pile is much larger than the ground deformation. Since the determination method of ultimate load based on the total settlement including such an elastic deformation of pile can overestimate the ultimate load, some organizations and researchers proposed the standards resulting from residual settlement, as systematically organized in Table 1. Moreover, the residual settlement, which is difference between total settlement and elastic settlement, can represent the ground properties so that it was selected for the determination of ultimate load.

According to ASSTHO, New York City, Louisiana, US Army Corps of Engineers, and Mansur and Kaufman (1958), 6.4 mm was used for the residual settlement as the ultimate load was determined, while the IS 2911 (2010) and Magnel (1948)'s standard was the residual settlement of 6 and 8 mm, respectively. Residual settlement of 12.7 mm was employed for assessing the ultimate load capacity by Boston and Woodward (1972), while according to Canada code and

Table 1 Settlement standards in pile load tests to assess the ultimate load capacity

Classification		Recommended by	Recommendation
Total Settlement	Total Settlement	IS 2911 (2010)	12 mm
		Germany; France; Belgium; Muns (1959)	20 mm
		Austria; Holland; New York City; Terzaghi and Peck (1967); Touma and Reese (1974)	25.4 mm
		Woodward (1972)	12.7~25.4 mm
	Relation with Pile Diameter	Roscoe (1957); De Beer (1964); BS 8004 (1986); JGS (2007); Tomlinson and Woodward (2014)	0.1D*
		De Beer (1964)	0.3D
		Van Impe (1988)	0.05D
	Incremental settlement / unit load	California; Chicago	0.254 mm/tonf
		Ohio	0.762 mm/tonf
		Raymond International	1.27 mm/tonf
Residual Settlement	Residual Settlement	IS 2911 (2010)	6 mm
		ASSHTO; New York City; Louisiana; US Army Corps of Engineers; Mansur and Kaufman (1958)	6.4 mm
		Magnel (1948)	8 mm
		Boston Building Code, Woodward (1972)	12.7 mm
		Canada	25 mm
		Christiani and Nielson of Denmark	38.1 mm
	Relation with Pile Diameter	DIN 4026 (1975)	0.025D
		DS 415 (1998)	0.1D
	Incremental settlement / unit load	New York City; Uniform Building Code (1982)	0.254 mm/tonf
		Raymond International	0.0762 mm/tonf

*D: Pile Diameter

Christiani and Nielson of Denmark, it was 25 and 38.1 mm, respectively. In Germany (DIN 4026 1975), the ultimate load was determined when a pile head settled to 2.5% of the pile diameter, while the failure load was calculated as a ratio of residual settlement to the pile diameter reached 10% in Denmark (DS 415 1998). The Raymond International standard was 0.0762 mm/tonf, which is residual incremental settlement per unit load, whereas the New York City and Uniform Building Code (1982)'s standard suggested that a 0.254 mm/tonf was employed to calculate ultimate load, which may be too large imposed load for the assessment (see Table 1).

3. Data acquisition

In order to investigate and evaluate pile stability under allowable load, the field experimental data on drilled shaft foundation measured from pile load tests in 20 different places at construction site were extensively collected for 8 year (from July 1997 to June 2004) in South Korea, thoroughly examined, and systematically tabulated in Table 2. The drilled shaft was installed in three different types of rock, i.e., igneous (granite), metamorphic (gneiss), and sedimentary rock (sandstone, mudstone, shale, or conglomerate). The diameter of drilled shaft was 1.0, 1.2, 1.5, and 1.8 m, and the length of the pile varied between 8.9 and 33.5 m. In general, a tip of the drilled shaft was socketed in bedrock with a depth of 1 m or more than the pile diameter. It was investigated that there was a direct correlation between the pile length and the depth of bearing layer. In other words, the design length of the drilled shaft was the same as the summation of the diameter of pile (or twice the pile diameter) and the depth of the bearing layer resulting from the boring investigation. The pile length socketed in rock was from 1.9 to 19.2 m. The maximum and minimum imposed load was 720 and 1,860 tonf, respectively. Three ways of imposed load on drilled shaft, i.e., concrete block, earth anchor, and reaction pile, were employed for the pile load tests in accordance with ASTM D1143 and KS F 2445. The earth anchors or concrete blocks were used for large loads needed, while reaction pile was suitable to small applied load required.

Table 2 Rock type and experimental results of pile load tests for drilled shaft socketed in rocks

Pile No.	Rock Type	Pile Diameter (m)	Pile Length (m)	Pile Length Socketed in Rock (m)	Imposed Load (tonf)[†]	Total Settlement (mm)	Residual Settlement (mm)	Type of Loading
P1	Granite	1.5	27.4	5.1	1,200	4.95	0.16	CB[*]
P2	Granite	1.2	11.1	5.0	1,000	6.50	1.53	EA[*]
P3	Granite	1.5	25.6	14.6	1,500	7.10	1.41	EA
P4	Granite	1.5	14.8	10.5	1,500	8.57	0.79	EA
P5	Granite	1.5	23.4	9.5	1,400	10.18	2.00	EA
P6	Gneiss	1.0	33.5	7.0	720	5.43	0.50	RP
P7	Gneiss	1.5	32.37	12.5	1,000	5.98	2.19	EA
P8	Gneiss	1.5	28.45	7.25	1,200	6.37	1.52	EA
P9	Biotitic Gneiss	1.5	31.87	19.2	1,600	6.82	1.52	CB
P10	Gneiss	1.5	19.3	4.8	1,350	7.10	1.41	EA
P11	Biotitic Gneiss	1.5	29.5	2.7	1,100	7.61	1.82	CB
P12	Gneiss	1.5	8.9	5.5	1,300	7.87	3.27	EA
P13	Gneiss	1.5	19.6	1.9	1,400	10.05	2.13	CB
P14	Granitic Gneiss	1.5	19.0	3.7	1,800	12.20	2.75	EA
P15	Gneiss	1.8	19.7	3.7	1,860	12.98	2.36	EA
P16	Sandstone	1.2	32.7	4.0	800	5.43	0.51	RP[*]
P17	Sandstone and Shale	1.0	24.5	8.0	1,400	6.857	1.34	EA
P18	Sandstone and Shale	1.0	24.0	9.0	1,400	7.563	2.037	EA
P19	Shale and Conglomerate	1.5	21.5	10.6	1,500	8.29	2.86	EA
P20	Mudstone and Sandstone	1.5	21.0	7.2	1,759	9.393	1.00	EA

[†] 1 tonf = 9.8067 kN; *CB: Concrete Block; EA: Earth Anchor; RP: Reaction Pile

4. Major factors on total settlement

4.1 Pile length socketed in bedrock

Total settlement of drilled shaft socketed in rocks is generally defined as the settlement when the 200% design load is imposed on the drilled shaft. Fig 1, Fig 2, Fig 3 and Fig 4 demonstrate the primary factors, e.g., the socketed pile length, imposed load, pile diameter, and shear stress, influenced on total settlement of drilled shaft socketed in bedrock based on statistical analysis. In Fig 1, the maximum and minimum total settlement was 12.98 mm in metamorphic rock and 4.95 mm in igneous rock, respectively. The longest pile length socketed in rock was 19.2 m in metamorphic rock. The average total settlement of drilled shaft socketed in igneous, metamorphic, and sedimentary rock was 7.5, 8.2, and 7.5 mm, respectively. It was observed that the total settlement of drilled shaft decreased with increasing the socketed pile length, which signifies that the longer embedded pile length resulted in less total settlement and this trend did not depend on the bedrock types.

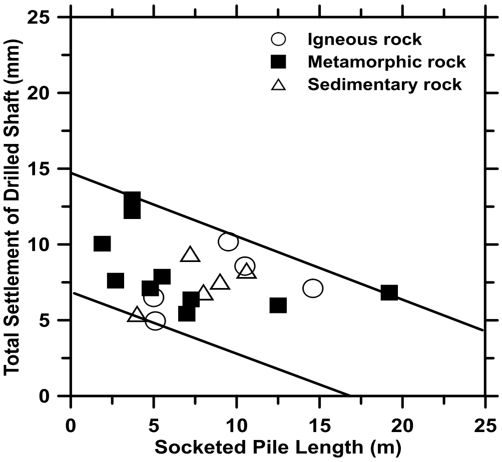


Fig. 1 Pile length socketed in bedrock

4.2 Imposed load

The total settlement of drilled shaft was plotted as a function of the imposed load, as presented in Fig 2. The total settlement linearly increased with the load applied on the drilled shaft, and the slope of the trend lines was 0.0058 mm/tonf, which was determined based on all experimental results in Table 2. The maximum total settlement of the drilled shaft was 12.98 mm at the imposed load of 1,860 tonf (18,240 kN), which was the maximum applied load on the drilled shaft. At the imposed load of 720 tonf (7,061 kN) the second minimum of the total settlement was measured to be 5.43 mm. Since the range of the imposed loads in the pile load tests was from 720 (7,061) to 1,860 tonf, (18,240 kN) which was two or three times the design load, the empirical relationship derived from the experimental data

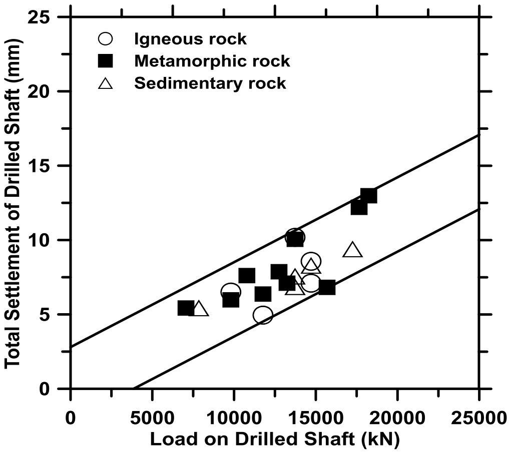


Fig. 2 Imposed load

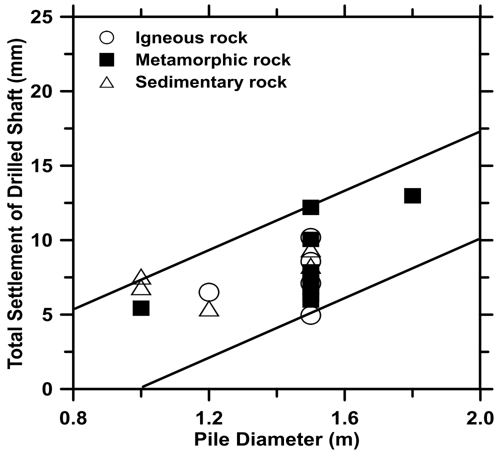


Fig. 3 Pile diameter

will be useful for evaluating the ultimate load. The yielding of the bearing layers did not occur at the maximum loads in most cases. This signifies that the tests were ended before the yielding of the bearing layer and the relationship in Fig 2 clearly represented the characteristics of the applied load-total settlement behavior before the yielding was reached. Although the large load was imposed on the drilled shaft socketed in bedrock, it was observed that the total settlement was much smaller than that of the driven pile. The primary reason for the small total settlement was due to the drilled shaft installed in bedrocks. Therefore, the standards summarized in Table 1 are not appropriate for the drilled shaft socketed in bedrocks to assess the ultimate load capacity.

4.3 Pile diameter

Fig. 3 shows the relationship between total settlement of drilled shaft and pile diameter. The range of pile diameter was between 1.0 and 1.8 m, but a pile diameter of 1.5 m was mainly used for the rock-socketed drilled shaft. Through statistical analysis, increasing trends wad observed; i.e., pile diameter increased with increasing total settlement. The maximum total settlement of drill shaft was 12.98 mm with the largest pile diameter (1.8 m) in metamorphic rock, while the minimum total settlement was measured to be 4.95 mm in igneous rock. The drilled shaft with large diameter can carry the large imposed loads, resulting in the large total settlement of the drilled shaft.

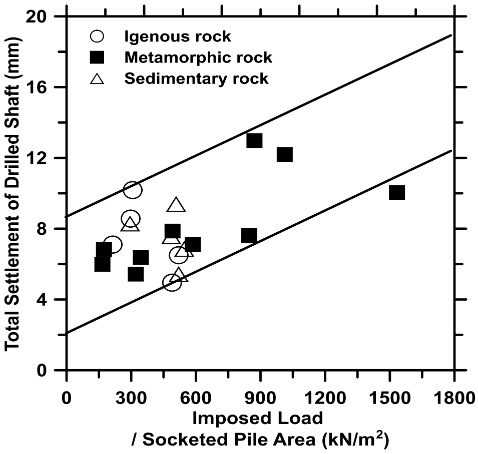


Fig. 4 Shear stress mobilized on drilled shaft

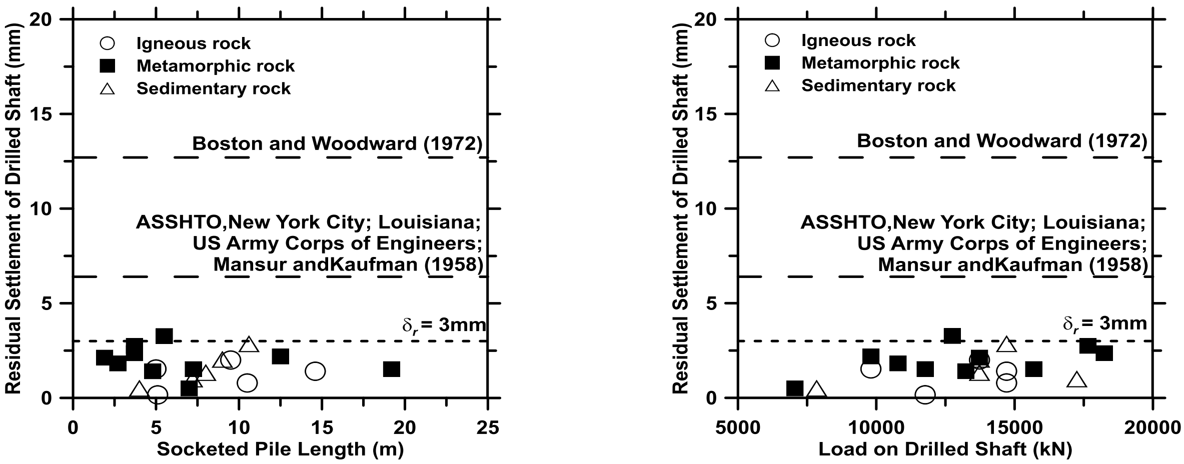
4.4 Shear stress mobilized on drilled shaft

In addition to above analyses based on the pile length socketed in bedrock, load imposed on drilled shaft, and pile diameter, a ratio of imposed load on drilled shaft to the socketed area was determined and compared with the total settlement of drilled shaft, as displayed in Fig 4. It was assumed that the imposed load was initially mobilized along the surface of drilled shaft and then transferred to the end bearing (Tomlinson and Woodward, 2014). Therefore, the initial imposed load was resisted at the embedded part of drilled shaft. The ratio of the imposed load on drilled shaft to the pile area socketed in the rock was defined as a shear stress mobilized along the surface area of socketed drilled shaft. The total settlement of drilled shaft almost linearly increased with increasing the shear stress along socketed drilled shaft. In particular, increasing trend in the total settlement of the drilled shaft socketed in metamorphic rock was clearly observed. The experimental results for igneous and sedimentary rock exhibit that the range of the ratio of imposed load to socketed pile area was relatively narrow.

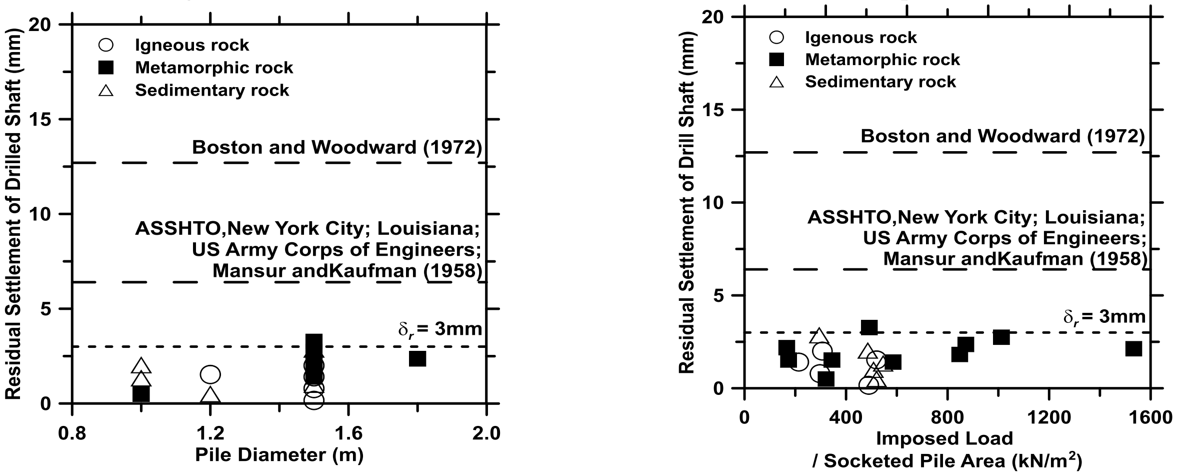
The summary of the observations and analyses was as follows; i.e., 1) the total settlement increased with decreasing the pile length socketed in bedrock, 2) the more load was imposed on drilled shaft, the more total settlement occurred, 3) the linear relationship between the total settlement of drilled shaft and the pile diameter was observed, and 4) the shear stress in bedrock increased with the total settlement of drilled shaft, and 5) the total settlement did not depend on the bedrock types, i.e., igneous, metamorphic, and sedimentary rock. These findings denote that the socketed pile length, imposed load, pile diameter, and shear stress in bedrock were primary factors influenced on the total settlement of drilled shaft because the elastic settlement of drilled shaft was included in the total settlement.

5. Characteristics of residual settlement

A residual settlement of drilled shaft was used to characterize the effect of the pile length socketed in bedrock,

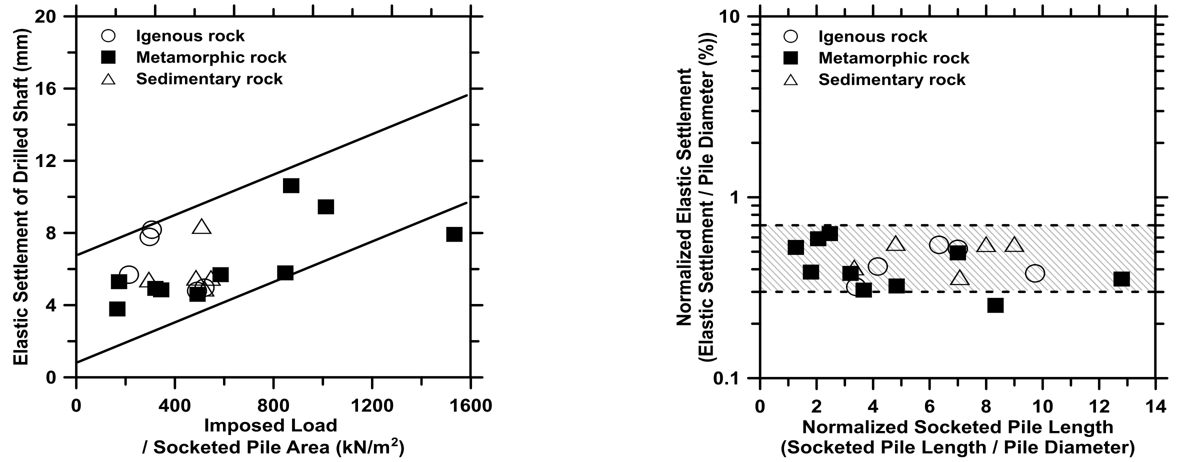


(a) Pile length socketed in bedrock (b) Imposed load



(c) Pile diameter (d) Shear stress in bedrock

Fig. 5 Relationship between primary factors and residual settlement of drilled shaft socketed in rock



(a) Behavior of elastic settlement with shear stress (b) Normalized elastic settlement

Fig. 6 Characteristics of elastic settlement of drilled shaft socketed in rock

load imposed on drilled shaft, pile diameter, and shear stress in bedrock, as displayed in Fig 5. The residual settlement was plotted as a function of the pile length socketed in bedrock and all experimental data were placed below 3 mm of the settlement except for the P12 (3.27 m) in Fig 5(a). The maximum and minimum pile length socketed in bedrock was 19.2 and 1.9 m in metamorphic rock, respectively. The constant pattern between the residual settlement of drilled shaft and the socketed pile length was observed.

Fig 5(b) demonstrates the trend between the residual settlement of drilled shaft and the imposed load, which was the same as that between the residual settlement and the socketed pile length in Fig 5(a). The maximum and minimum residual settlement of drilled shaft was 3.27 and 0.16 mm, respectively, and the residual settlement of drilled shaft was independent on the imposed load. Fig. 5(c) is the relationship between the residual settlement and pile diameter and all collected data were also placed below 3 mm of the settlement. In Fig 5(d), the residual settlement of drilled shaft was drawn as a function of the shear stress in bedrock. The average residual settlement of drilled embedded in igneous, metamorphic, and sedimentary rock was 1.2, 1.9, and 1.5 mm, respectively. Since the maximum residual settlement of drilled shaft was approximately 47% of the residual settlement of the ASSHTO, which was the second smallest value among all standards, it was impossible to determine the ultimate load based on the criterion in Table 1.

From the analyses based on the residual settlement, it was concluded that 1) the residual settlement was completely independent on the rock types, i.e., igneous, metamorphic, and sedimentary rock, 2) the socketed pile length, imposed load, pile diameter, and shear stress in bedrock did not influence the residual settlement of drilled shaft because the constant trends between residual settlement and independent values were drawn, and 3) the residual settlement results of drilled shaft for determining the ultimate load were much smaller than the standards proposed by organizations and researchers in Table 1.

6. Characteristics of elastic settlement

Although the existing standards for assessment of ultimate load were proposed based on the total or residual settlement, the elastic settlement, which can be defined as a difference between the total settlement and residual settlement, can be used to investigate the characteristic of drilled shaft socketed in bedrock. Fig 6(a) shows the relationship between the elastic settlement and the imposed load divided by the socketed pile area, which was the shear stress in bedrock. The patterns were very similar to the trend in Fig 2, which was the linear relationship between the elastic settlement of drilled shaft and the shear stress in bedrock. The relationship between normalized elastic settlement and normalized socketed pile length is presented in Fig 6(b). Here, normalized socketed pile length can be defined as a ratio of the socketed pile length to the pile diameter. Primary reason for the use of the socketed pile length is due to the assumption that friction was mobilized at the embedded part of the drilled shaft. The normalized elastic settlement was defined as a ratio of the elastic settlement to the pile diameter. Most experimental results from the pile load tests were located between 0.3 and 0.7% of the normalized elastic settlement, which denotes that 1) the incremental rate of elastic settlement with respect to pile diameter was constant and 2) the elastic settlement increased with increasing the socketed pile length within a range of 0.3 ~ 0.7% of pile diameter.

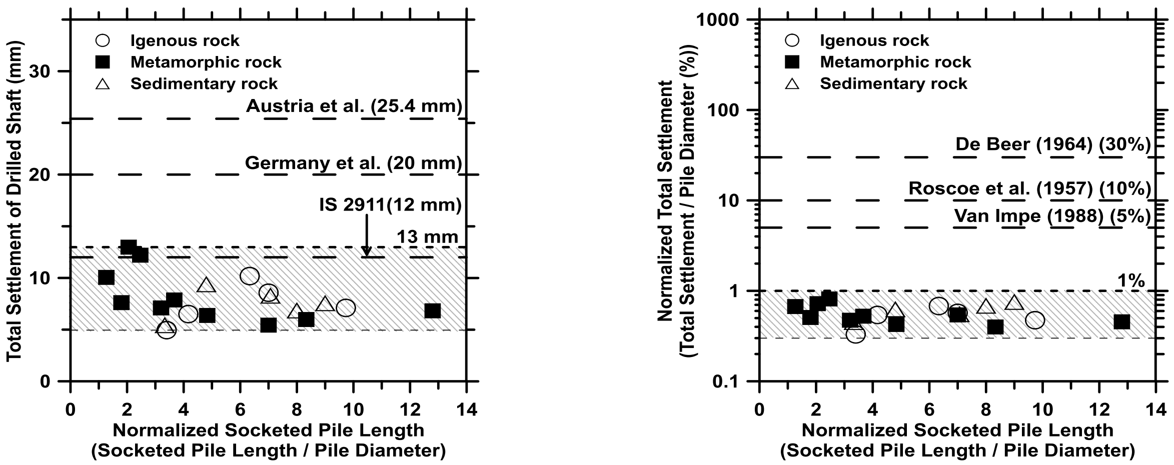
7. Discussion

The standards of total or residual settlement for determination of the ultimate load capacity of the piles were systematically summarized above. However, these settlement criteria were only employed to assess the ultimate load of the driven pile or the cast-in-place pile. Therefore, the standards were too high to estimate the ultimate load of the drilled shaft socketed in bedrock. Regrettably, there is no available standard for the drilled shaft. The experimental data are compared with the standards developed by organizations and researchers and the new criteria of total or residual settlement are proposed to determine the ultimate load capacity of the drilled shaft socketed in rocks.

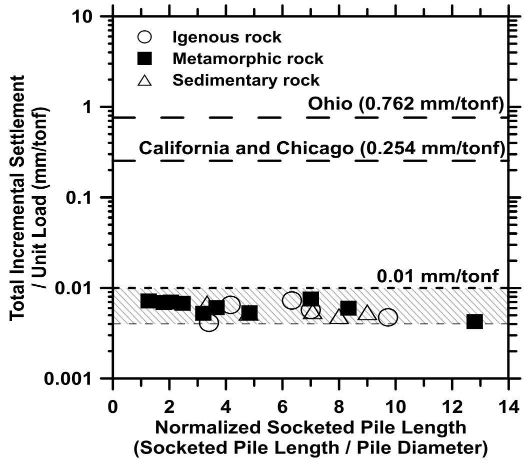
7.1 Settlement criteria based on total settlement

In order to investigate the limit of the total settlement for the assessment of the ultimate load capacity of drilled shaft, the total settlement was plotted as a function of a ratio of the socketed pile length to the pile diameter, which was similar concept to the slenderness ratio (resistance to buckling or bending), as demonstrated in Fig 7. All total settlements were placed between 4.9 mm and 12.98 mm and the ratio of the socketed pile length to the pile diameter was 1.27 and 12.8, as shown in Fig 7(a). The measured total settlement of drilled shaft was smaller than the standards by the researchers and organizations except for IS 2911 (2010), as demonstrated in Table 1. In metamorphic rock, it was observed that the total settlement exponentially decreased and converged with increasing the socketed ratio, while there was no pattern for igneous and sedimentary rocks in Fig 7(a). Although the Indian Standard, whose standard was 12 mm of total settlement, and the minimum value (12.7 mm) of total settlement proposed by Woodward (1972) were close to the maximum total settlement of experimental data, other criteria in Table 1 were higher than the test results. Therefore, new criterion based on the total settlement must be required to assess the appropriate ultimate load of the drilled shaft socketed in rocks. The total settlement of 13 mm is a proper value for the drilled shaft socketed in three types of rock because all total settlement measurements were below 13 mm.

In Fig 7(b), the vertical axis signifies the normalized total settlement, which is a ratio of the total settlement of the drilled shaft to the pile diameter, and the horizontal axis denotes a ratio of the socketed pile length to the pile diameter. De Beer (1964)'s standard was that the failure load for the cast-in-place pile was determined at moment when a pile head of 30% of pile diameter was settled. Comparison between these normalized total settlement criteria and the measured total settlement of drilled shaft shows that the normalized total settlement ranges from 0.3 to 1.0%, which was much smaller than the existing standards as shown in Fig 7(b) and then the normalized total settlement criterion for the assessment of ultimate load capacity of the drilled shaft must be modified. Since normalized total settlement of 30% was extremely overestimated for rock-socketed drilled shaft, some organizations and researchers developed that the ultimate load was determined when a ratio of residual settlement to the pile diameter reached 10% (Roscoe 1957, BS 8004 1986, JGS 2007, Tomlinson and Woodward 2014). The



(a) Total settlement (b) Normalized total settlement



(c) Total incremental settlement per unit load

Fig. 7 Comparison between experimental total settlements and the standards Note:1 tonf = 9.8067 kN

Table 3 Settlement criteria in pile load tests to assess the bearing capacity of drilled shaft socketed in rock

Classification		Recommendation
Total Settlement	Total Settlement	13 mm
	Relation with Pile Diameter	0.01D*
	Incremental settlement / unit load	0.01 mm/tonf**
Residual Settlement	Residual Settlement	3 mm
	Relation with Pile Diameter	0.003D
	Incremental settlement / unit load	0.003 mm/tonf

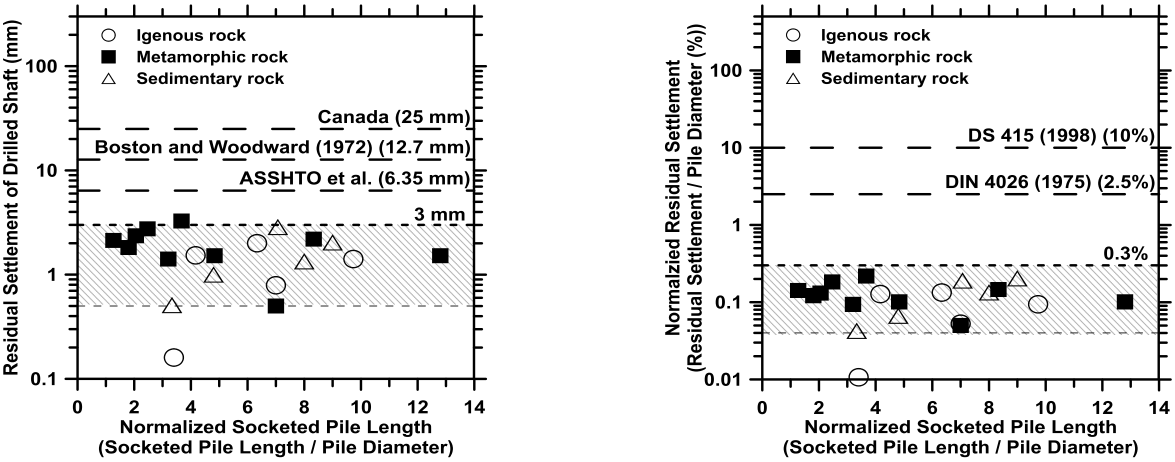
*D: pile diameter/ **1 tonf = 9.8067 kN

standard for the normalized total settlement proposed by Van Impe (1988) was 5% of pile diameter, which was also higher than the experimental results. Since the observed data of the normalized total settlement were between 0.3 and 1.0%, the limit of the normalized total settlement of 1.0% is a suitable one for new criterion to assess the ultimate load of drilled shaft socketed in the rocks.

Fig 7(c) shows the relationship between the incremental settlement per unit load and a ratio of the socketed pile length to the pile diameter. The total settlement of the drilled shaft was used to calculate a ratio of the total incremental settlement to unit load, and the incremental load per unit load was located between 0.004 and 0.01 mm/tonf, which was much smaller than the standards by California and Chicago (0.254 mm/tonf), Ohio (0.762 mm/tonf), and the Raymond International (1.27 mm/tonf). Therefore, based on the comparison between the existing standards and the experimental results of drilled shaft socketed in various rocks, it was proposed that 0.01 mm/tonf is new criterion to assess the ultimate load of drilled shaft socketed in rocks. To assess the ultimate load capacity of rock-socketed drilled shaft, new criteria based on total settlement are summarized in Table 3.

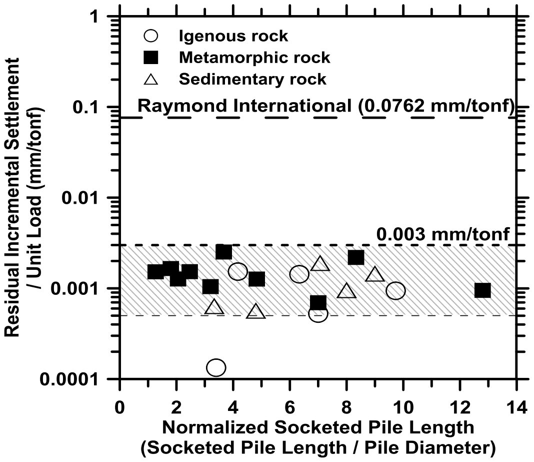
7.2 Residual settlement criteria

Fig 8 displays the comparison between residual settlement of drilled shaft from plie load tests and the existing standards summarized in Table 1. In Fig 8(a), all residual settlement data of the drilled shaft were expressed as a function of a ratio of pile length socketed in bedrock to the pile diameter, and most residual settlement results were located from 0.5 to 3 mm except for P1 (0.16 mm), which was extremely small residual settlement compared with others so that the result was removed for analysis. According to the ASSTHO, New York City, Louisiana, US Army Corps of Engineers, and Mansur and Kaufman (1958), the residual settlement of 6.4 mm (0.25 inch) was used to



(a) Residual settlement

(b) Normalized residual settlement



(c) Residual incremental settlement per unit load

Fig. 8 Comparison between experimental results based on residual settlement and the standards

determine the ultimate load of the pile. Boston and Woodward (1972)'s standard was 12.7 mm, and residual settlement of 25 mm was proposed by Canada. There was no specific trend for all three types of rock and the residual settlement of drilled shaft was not dependent on the socketed pile length, as shown in Fig 8(a). A fact that the maximum residual settlement of drilled shaft was 3 mm indicates that the new criterion must be needed to determine the ultimate load capacity of drilled shaft socketed in rocks, and this value is a proper limit of the residual settlement to assess ultimate load of drilled shaft.

In Fig. 8(b), the residual settlement of the drilled shaft was employed to calculate the normalized settlement, which can be defined as a ratio of residual settlement of drilled shaft to the pile diameter. The normalized residual settlement was between 0.04 and 0.3% except for P1 (0.01%), and the maximum value was also much smaller than the standards by the DIN 4026 (1975) and DS 415 (1998). According to the DIN 4026 (1975), the ultimate load was calculated at a residual settlement of 2.5% of the pile diameter. The DS 415 (1998) proposed that the failure load was determined at moment when pile head was plastically settled to a 10% of the pile diameter. However, those criteria cannot apply to the drilled shaft socketed in rocks, as presented in Fig. 8(b). Therefore, the standard must be created and the suitable limit of normalized residual settlement is 0.3%.

As displayed in Fig. 8(c), the vertical axis denotes the ratio of the residual incremental settlement of drilled shaft to the unit load. According to the criteria in Table 1, the incremental settlement per unit load was 0.0762 mm/tonf (the Raymond International) and 0.254 mm/tonf (New York City; Uniform Building Code (1982)). These standards were considerably larger than 0.003 mm/tonf, which was the maximum value of the residual incremental settlement per unit load determined from the test data. The residual incremental settlement per unit load was 0.003 mm/tonf, which is an appropriate value for assessment of the ultimate load of drilled shaft socketed in rocks. Residual settlement criteria in pile load tests to assess the ultimate load capacity of rock-socketed drilled shaft are summarized in Table 3.

7.3 Design of pile length socketed in rock

Fig. 9 shows the design chart for socketed pile length in rocks based on the total settlement. The vertical axis is a ratio of total settlement to the socketed pile length, and horizontal axis is the normalized socketed pile length. It was observed that a ratio of total settlement to the socketed pile length exponentially decreased with increasing the

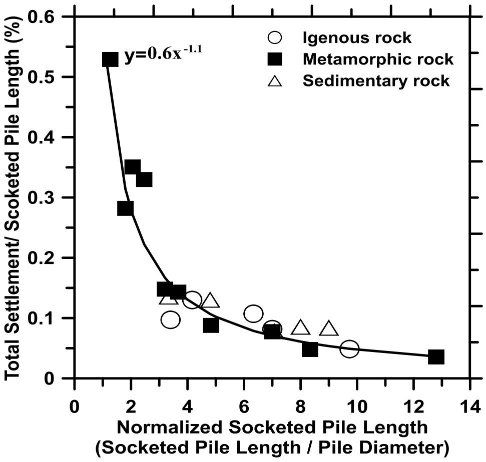


Fig. 9 Design chart for socketed pile length in rocks based on total settlement

normalized socketed pile length and then converged to a certain value for all three types of bedrock, i.e., igneous, metamorphic, and sedimentary rock. This observation signifies that 1) the installation of the long drilled shaft socketed in bedrock is not necessary because there is no effect of reduction in the total settlement and 2) the empirical equation included in Fig 9 can be employed for the design of the pile length socketed in rock. Based on the design chart, the procedures of socketed pile length are as follows. First, normalized socketed pile length is chosen between 1 and 13. Second, the allowable total settlement is selected less than 13 mm. Finally, the proper pile length socketed in rock can be calculated by substituting the designed normalized socketed pile length and total settlement in the empirical equation and then pile diameter can be also determined. The minimum pile length socketed in rock was approximately 3.5 times the pile diameter because the point of maximum curvature was observed at a ratio of total settlement to the socketed pile length of 0.15% and the normalized socketed pile length of 3.5. Although the use of 3.5 and 0.15% is the most economical one, the design curve greater than 3.5 and less than 0.15% can be used for the design in a conservative way.

8. Conclusions

In this paper, to analyze and investigate the total and residual settlement features of drilled shaft socketed in bedrock for determination of ultimate load capacity, the field test data of pile load tests were gathered and tabulated. Based on analysis and comparison between the experimental results of drilled shaft and the standards, the following conclusions are made:

- The total settlement of drilled shaft was directly proportional to load imposed on drilled shaft, pile diameter, and shear stress in bedrock, while that was inversely proportional to the pile length socketed in bedrock. The pattern of the total settlement of drilled shaft was independent on the bedrock types, i.e., igneous, metamorphic, and sedimentary rock.
- The residual settlement did not depend on the bedrock types, the socketed pile length, the imposed load, the pile diameter, and the shear stress in bedrock. All residual settlement results measured from the pile load test was below 3 mm, which was smaller than the standards and would be useful to determine the ultimate load of drilled shaft socketed in rock.
- The elastic settlement, which was difference between the total and the residual settlements, were used for analyses. The elastic settlement with respect to pile diameter increased within a range of 0.3 ~ 0.7% of pile diameter as increase in the socketed pile length, which denotes the incremental rate of elastic settlement was constant and the elastic settlement increased with the pile length socketed in bedrock within a range of 0.3 ~ 0.7% of pile diameter.
- Comparison between the total settlement of drilled shaft and the criteria proposed by organizations and researchers shows that 1) the existing standards must be modified for rock-socketed drilled shaft and 2) the appropriate limit of total settlement, normalized total settlement, and incremental total settlement per unit load was 13 mm, 1.0%, and 0.01 mm/tonf, respectively, in order to assess the ultimate load capacity of rock-socketed drilled shaft.
- Based on extensive analyses on the residual settlement data, it was concluded that new criteria were needed for the drilled shaft socketed in rocks. The residual settlement of 3 mm, the normalized residual settlement of 0.3%, and the residual incremental settlement per unit load of 0.003 mm/tonf were the suitable values for the determination of the ultimate load capacity of drilled shaft socketed in rocks.
- The design chart for pile length socketed in rocks was proposed based on the total settlement. It was found that the minimum pile length socketed in rock was about 3.5 times the pile diameter. Based on the design chart and given values of pile diameter and the proper limit of total settlement, the socketed pile length can be determined. Although the proposed design chart can be used for any rock types, the prerequisite is required that the rock has sufficient strength and can be used as a pile foundation for structures.

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