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Pile groups subjected to abrupt collapse of retaining structure

Author:

Rajesh Prasad Shukla, M.Tech, CE
Department of Civil and Infrastructure Engineering
Adani Institute of Infrastructure Engineering
Ahmedabad Gujrat, India
shuklarajesh4687@gmail.com

Preliminary note

Rajesh Prasad Shukla

Pile groups subjected to abrupt collapse of retaining structure

Excavations supported by retaining structures are very common in the construction of new structures in urban and hilly areas. This paper presents behaviour of model piles of various configurations, when exposed to soil movement induced by collapse of the retaining structure. The performance of pile groups varies significantly with the distance between the pile group and the retaining structure. A pile row parallel to the retaining structure experiences large displacement as compared to pile rows that are perpendicular to the structure.

Key words:
soil movement, pile, retaining structure, displacement, group configuration

Prethodno priopćenje

Rajesh Prasad Shukla

Ponašanje grupe pilota pri naglom rušenju potporne konstrukcije

Pri izvođenju novih građevina u urbanim područjima i na padinama često se primjenjuju postupci podupiranja iskopa pomoću odgovarajućih potpornih konstrukcija. U ovom je radu prikazano ponašanje modela pilota raznih konfiguracija pri pomicanju tla uslijed rušenja potporne konstrukcije. Ponašanje grupe pilota u velikoj mjeri ovisi o udaljenosti između grupe pilota i potporne konstrukcije. Pojavljuje se veći pomak kod reda pilota koji je paralelan s potpornom konstrukcijom nego kod reda pilota koji je postavljen okomito u odnosu na potpornu konstrukciju.

Ključne riječi:
pomicanje tla, pilot, potporna konstrukcija, pomak, konfiguracije grupe

Vorherige Mitteilung

Rajesh Prasad Shukla

Verhalten von Pfeilern bei plötzlichem Einsturz einer Stützkonstruktion

Bei der Ausführung neuer Gebäude in städtischen Gebieten und an Hängen werden häufig Verfahren der Unterstützung des Aushubs durch entsprechende Stützkonstruktionen angewendet. In dieser Abhandlung wird das Verhalten von Pfeilermodellen unterschiedlicher Konfigurationen bei Erdbewegung infolge des Einsturzes der Stützkonstruktion dargestellt. Das Verhalten der Pfeilergruppen hängt weitgehend von den Abständen zwischen den Pfeilergruppen und der Stützkonstruktion ab. Bei Pfeilerreihen, die parallel zur Stützkonstruktion verlaufen, treten größere Verschiebungen auf, als bei Pfeilerreihen, die senkrecht zur Stützkonstruktion angeordnet sind.

Schlüsselwörter:
Erdbewegung, Pfeiler, Stützkonstruktion, Verschiebung, Konfiguration der Gruppe

1. Introduction

Heavy structures are generally supported by pile foundations. Pile foundations are also effective in bypassing loose soil present at shallow depths [1]. Based on load transfer mechanism, a pile foundation can be categorized into: active piles and passive piles. Active piles are loaded on the top and the load is transferred from piles to the soil. In the case of passive piles, the load transfer is from the soil to the pile. Passive piles can sustain large lateral loads caused by soil movement initiated due to landslides, embankment loading, soil excavation, underground construction, tunnelling and various other activities [2].

Sometimes, construction requires large excavation that can alter the existing soil conditions, thereby affecting behaviour of foundations as well as that of the structure. Deep excavation and collapse of retaining wall in the vicinity of existing piles decrease the end bearing capacity and lateral confinement of piles. The release of vertical pressure may lead to ground subsidence, eventually resulting in a decrease of shaft friction, distress and sometimes complete failure of the retaining structure and/or foundations [3]. Piles adjacent to unsupported excavation experience higher settlement and lateral displacement compared to those adjacent to a supported excavation. Poulos, [4] considered various possible cases of soil movement and used the simplified boundary element analysis to derive a solution. The analysis revealed that the soil movement itself does not affect the load carrying capacity of deep foundations. However, its significance in design can not be discarded since it affects integrity of pile foundations. In some pile foundation cases reported in literature the stability of the structure and foundations was affected by soil movement. This is due to reduction in density of soil and confining pressure caused by soil movement induced by excavation [5-8]. Ong [7] measured pre-failure and post-failure deflection of a full-scale instrumented concrete pile group subjected to lateral soil movement caused by slope failure.

Researchers have developed analytical, theoretical and experimental approaches to predict the response of pile foundations exposed to soil movement. However, most of the studies considered the cases of excavations supported by retaining structures [8-25]. Abbas et al. [26] performed numerical analysis using Plaxis and found that the group configuration has a significant effect on the performance of pile groups subjected to lateral loading. Various design charts were prepared to evaluate the response of piles near strutted excavations [27, 28]. A few studies determined the settlement of loaded pile groups under soil movement induced by excavation [29, 30]. The maximum bending moment of piles and pile deformation in passive piles decrease with an increase in the over-consolidation ratio [31].

Literature review reveals that most of the studies were conducted on piles under supported excavation and, also, that no working load was considered. It is also possible that a retaining structure preventing soil movement near the piles can fail itself due to excavation or for any other reason, and subsequently allow easy movement of the retained soil. In such cases, the pattern of soil movement will depend on the nature of failure of the retaining structure. Soil movement is slow in case of progressive failure of a retaining structure, while this movement is really very fast in the case of abrupt collapse of retaining structure. The mode of deformation of retaining structures is affected by properties of the ground, support system, and construction practice. Construction activities at the construction site are unpredictable and it is assumed in the present study that construction activities have induced sudden collapse of the retaining structure. This condition may prevail in hilly regions as well, where retaining walls and other arrangements are used to retain soil movement and provide stability near existing foundations and structures.

In the present study, model tests were performed to determine response of single model piles and pile groups subjected to soil movement induced due to an abrupt collapse of a retaining structure. Tests were conducted on pile groups (2 × 1, 1 × 2, 3 × 1, 1 × 3 and 2 × 2) at the varying spacing of 3, 4 and 6 times the pile diameter. The distance between the retaining structure and pile groups was also varied and studied. Lateral displacement of piles was measured and presented in a dimensionless form.

2. Experimental setup and testing program

A schematic view of the model tank with complete setup is shown in Figure 1 (not to scale). The tank (1 m × 1 m × 1 m) is made up of 6 mm thick steel plates. The experimental setup consists of a model tank, model piles, measuring devices like

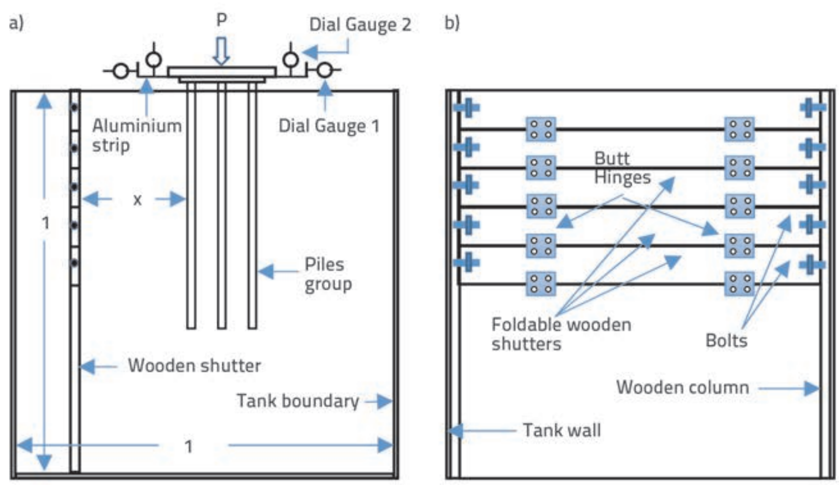

Figure 1. Details of experimental setup: a) Representative experimental setup; b) Wooden shutter arrangement

dial gauges, an arrangement for load application, ancillary equipment, sand pouring device and a wooden shutter attached to the tank wall.

A wooden shutter was designed to simulate an abrupt collapse of the retaining structure and was installed in the model tank (Figure 1b). The Wooden shutter has five rotatable parts, and each part is interconnected through two "butt hinges". These hinges allow every part to rotate in outward direction only, thus simulating failure of the retaining structure. The shutter is connected to the tank via two wooden columns. Each movable part is attached separately to the wooden columns by means of two bolts. Loosening of these bolts allows the rotatable part to fall freely without affecting the remaining lower parts. The wooden columns are firmly fixed to the tank by nut and bolt systems. The depth of soil movement is expressed in terms of pile length. The depth ratio of soil movement is the ratio of the height of retaining structure collapsed to the length of the pile. A detail of depth ratio of soil movement is presented in Table 1.

Table 1. Critical height of retaining structure

Length of pile, L [cm]	Number of a wooden shutter loosen	Height of retaining structure, H_c [cm]	Depth ratio of soil movement (H_c/L)
32	0	0	0
	1	10	0.312
	2	22	0.687
64	0	0	0
	1	10	0.156
	2	22	0.344
	3	34	0.532

Indian standard grade-II sand was used as foundation material. Index properties of soil are shown in Table 2. This sand is popularly known as "Ennore" sand and its behaviour is considered to be free from time effect. The loss on extraction with hot HCl is only 0.11 %. The sieve analysis result is shown in Figure 2. This sand consists of sub-angular shaped grains of greyish white colour.

The model piles were fabricated using a hollow circular aluminium tube having an outer and internal diameter of 32.0 and 30.0 mm, respectively. To change the embedment ratio, the length of pile was varied, while pile diameter was kept constant throughout the testing. Two pile lengths, 320 mm and 640 mm, were used to achieve an embedment ratio of 10 and 20, respectively. Piles were made in such a way that they can split longitudinally into two pieces. This facilitated fixing of strain gauges inside the pile surface. Piles were threaded at the top to enable connection to pile caps.

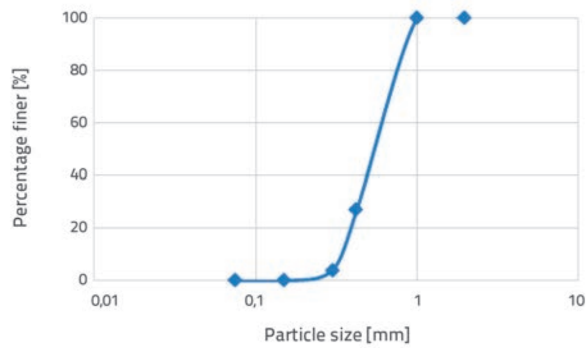

Figure 2. Grain size distribution of sand used in the study

Pile displacement was measured by four dial gauges with magnetic base and with the sensitivity of 0.01 mm. Dial gauges 1 and 2 were used to measure lateral and vertical displacement of piles, respectively. Fastenings and accessories were used to fix dial gauges to the desired location, and to connect the piles to the pile cap. C-clamps and other nut-bolt systems were used to assemble and detach pile groups from the model tank. Plenty of other ancillary devices were also used to assist in proper realisation of the experiment.

3. Experimental procedure

Compression tests were conducted to evaluate capacity of pile groups. Based on their results, a safe load was determined for a single pile and for pile groups. Safe loads determined by compression tests were applied on piles subjected to abrupt lateral soil movement. Compression test details are presented in paper published by Shukla and Patra [32]. The rain fall method, wherein sand is dropped from a fixed height, was used to pour the sand into the tank in order to achieve the essential density. Researchers have already used this technique to achieve reproducible densities [33-34].

Table 2. Properties of sand used in study

Property	Description	Property	Description
Maximum density	16.8 kN/m³	Unit weight	15.61 kN/m³
minimum void ratio (e_{min})	0.58	Void ratio (e)	0.672
Minimum density	14.4 kN/m³	Coefficient of curvature	0.97
Maximum void ratio (e_{max})	0.78	Uniformity coefficient	1.70
Relative density of sand	54.3 %	Pile soil friction (δ)	20.50
Specific gravity	2.64	Angle of internal friction	34^0

All piles were marked up to two-third of embedment depth. Piles were assembled with pile cap outside the tank. Tank walls were marked to identify the tip level of piles when sand is filled. After filling the tank up to the marked level, piles were suspended in the tank using four C-clamps and two flat steel plates. This step requires high precision to maintain the pile cap perfectly level. The level of pile cap was checked using a spirit leveller to avoid tilting. This helps in maintaining the vertical loading on the pile cap. The sand filling was restarted and continued until it reached the marked level on the pile periphery. Since piles were sufficiently embedded in the sand by that time, C-claps were loosened, and both flat plates were detached carefully from the pile cap. The level of pile cap was checked again to confirm its horizontal alignment. The sand pouring was restarted and it continued up to the top level of the tank. Subsequently, the level of the cap was checked once again.

The dial gauges were placed in the required position using two iron plates and a steel column. Two L-shaped and two flat aluminium strips were attached to the pile cap by means of the nut-bolt system. The needle of two dial gauges (measuring the lateral displacement) was supported on the L-shaped strip, while those of the other two dial gauges (measuring the vertical displacement) were supported on the flat aluminium strips. This dial gauge and aluminium strip arrangement was used so that the load can be applied directly on pile cap. The level of pile cap was checked again and a flat circular plate was fixed onto the pile cap. This plate supported the loading in case of a single pile and pile rows, while in the case of square pile groups, the load was directly applied onto the pile cap. The safe pile load, which was already evaluated by compression test, was applied to the centre of pile cap. The sand density was checked before and after applying the loading to confirm that the loading stage did not alter the density of sand. A dynamic penetrometer was used to assess the density of sand. The setup was left undisturbed for some time to allow settlement of piles after load application. The testing was restarted once the dial gauge readings became stable.

To simulate collapse of the retaining structure, the top part of the wooden shutter was allowed to fall. After sufficient time lapse, dial gauge readings were measured and noted. For piles of embedment ratio 10, the excavation was continued up to the depth ratio of 0.65, whereas in the case of piles with embedment ratio 20, excavation was performed up to the depth ratio of 0.52. Vertical and horizontal displacement values were read directly from dial gauge. Displaced soil profiles were measured using vertical lines drawn on the tank wall. These vertical lines drawn on tank wall denote lateral distance from the retaining structure.

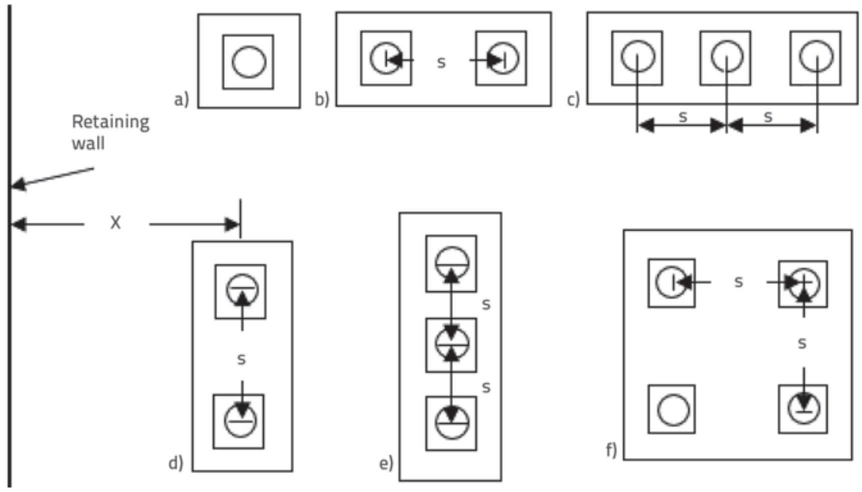

Figure 3. Pile group configurations considered in the study: a) Single pile; b) 1 × 2; c) 1 × 3; d) 2 × 1; e) 3 × 1; f) 2 × 2

Pile group configurations used in the study are shown in Figure 3. The distance (X) between piles and retaining wall is measured between the centre of the first row of piles and the retaining wall. Pile groups, 2 × 1 and 3 × 1 are parallel to the retaining structure, while groups, 1 × 2 and 1 × 3 are perpendicular to the retaining structure. A total of six configurations were considered in the analysis. A few tests were repeated to validate the results.

4. Results and discussion

Lateral displacement (LD) of piles is represented in dimensionless form as a ratio of pile displacement to the height of the failed retaining structure. Similarly, the distance between piles and the retaining structure was also expressed in terms of height of the retaining structure. Figure 4 shows instrumental setup for an unloaded single pile before and after collapse of the retaining structure. In the previous studies, the forces on the piles increased progressively with an increase in the depth of soil movement due to progressive failure of the retaining structure [3, 21]. However, in the present study, lateral loading on pile per unit length is increased rapidly due to an abrupt collapse of the retaining structure. Contrary to previous studies, the soil movement is induced due to collapse of the retaining wall rather than due to excavation activity [8-22]. The results of this study are not directly scalable to full-scale conditions because of the low pressure (high dilation/low stiffness) response in the present study.

The movement of sand was also measured in several tests and it was found that the sand slope is not an exactly free slope, although it was very close to free slope. Figure 5 shows a typical profile of slopes for different height of collapsed retaining structure in case of pile group of 2 x 1 resting at a distance of 20.4 cm from the retaining structure. The profile of soil movement varies with a number of factors. However, it depends significantly on the height (H_c) of the collapsed retaining wall. The measured

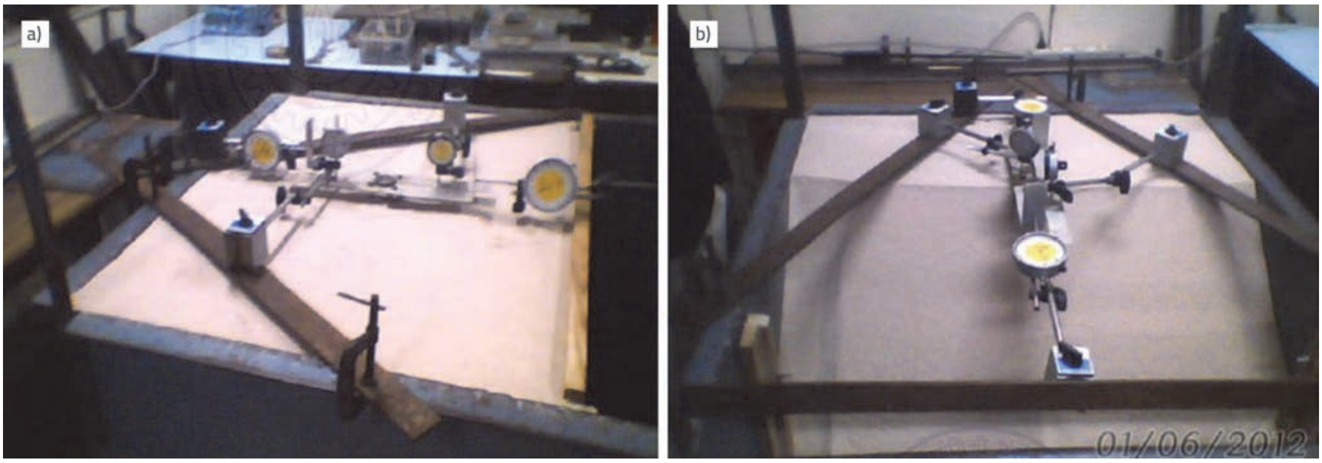

Figure 4. Instrumented setup for a pile without loading: a) Before collapse; b) after collapse of retaining wall

angle "α" increased significantly when H_c/L increased from 0.156 to 0.344. However, the angle α increases only marginally if H_c/L is increased to 0.534. Further extensive work is required to determine the profile of soil movement for different values of relative density, the distance between piles and retaining structure, group interaction effect of piles and height of collapsed retaining wall using large scale testing facilities.

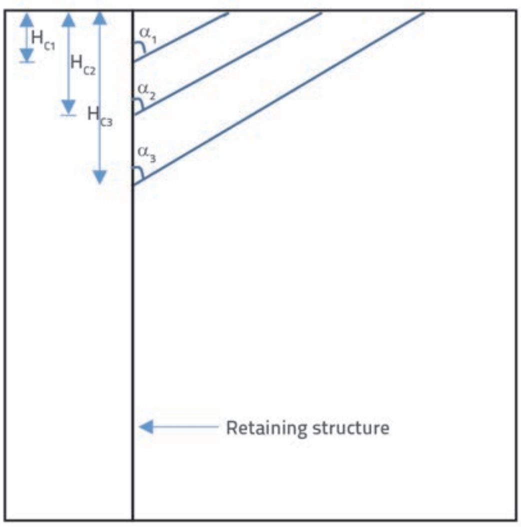

Figure 5. Profile of soil movement with height of collapsed retaining structure

4.1. Single Piles

Lateral displacement of single piles is shown in Figure 6. Irrespective of other parameters, displacements of a single pile increased with an increase in height of the collapsed retaining structure. Likewise, the displacements increase with a decrease in the distance between the pile and the retaining structure.
For a given depth ratio of soil movement, lateral displacement is large for the pile having a higher embedment ratio (L/d = 20) as compared to piles with lower embedment ratio (L/d = 10).

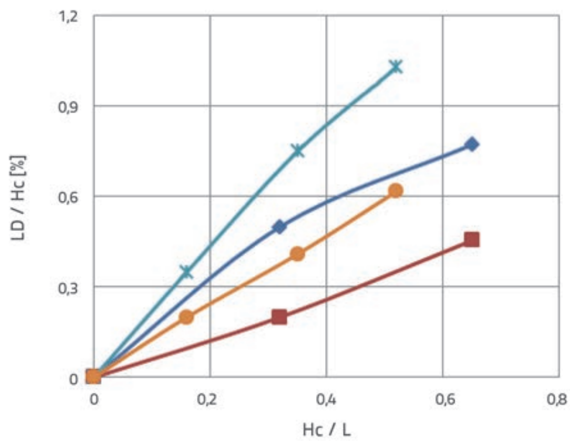

Figure 6. Lateral displacement of single pile

4.2. Pile groups

The behaviour of pile groups depends on embedment ratio of the pile (L/d), the distance between the pile group and the retaining structure (X), the depth ratio of soil movement (H_c/L), and the loading condition. Apart from these factors, the behaviour of pile group also depends on the group interaction effect, which can be analysed by considering the group configuration, pile spacing (s) and the number of piles (n) within a pile group. The soil arching affects behaviour of the pile group. In the cohesionless soil, arching effects depend on the location of the first row of the pile group, and it reduces significantly for trailing piles [35]. The first row of piles acts as a shield against soil movement and reduces both lateral and vertical displacement.

4.2.1. Effect of depth ratio of soil movement

The effect of depth ratio of soil movement on lateral displacement of pile groups is presented in Figure 7 for various pile groups. Similar to behaviour of a single pile, the displacement of pile group increases with an increase in the depth ratio of soil movement (H_c/L). The lateral force acting on piles increases with an increase in height of the collapsed retaining structure, eventually resulting in an increase in lateral displacement. After a certain depth ratio of soil movement, the rate of increase in displacement is reduced for piles group of embedment ratio 20. In the case of piles of small embedment (L/d = 10), the displacement increases with the depth ratio of soil movement.

For a pile group of embedment ratio 20, placed perpendicular to the retaining structure, an increase in the depth ratio of soil movement from 0.344 to 0.52 does not increase lateral displacement of piles significantly. Though lateral displacements are comparatively large in the present case, the trend of curves is very much similar to that presented by Dominic [3]. The magnitude of displacement is large as piles are subjected to the soil movement of relatively large volume and high velocity. Pile

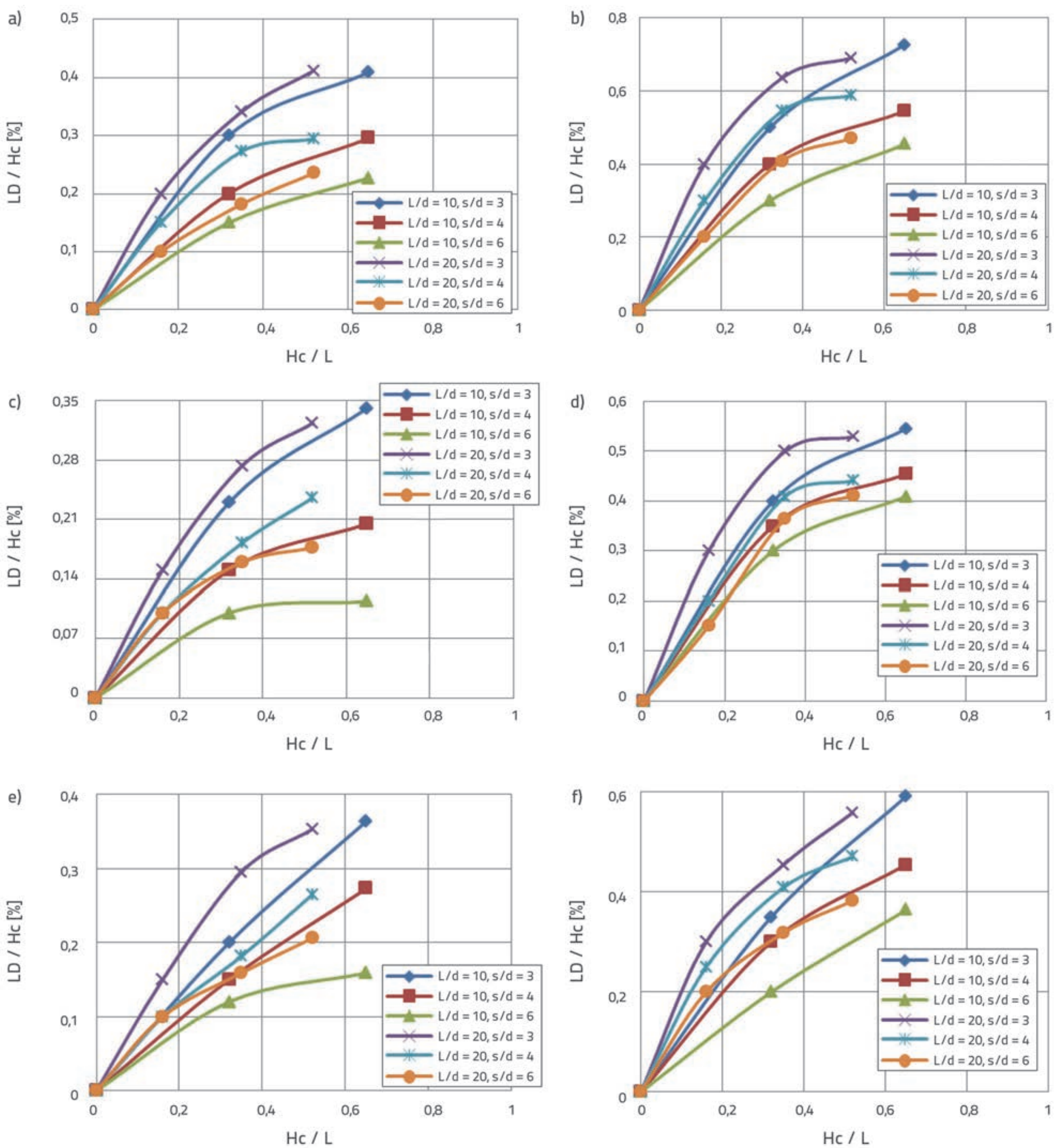

Figure 7. Effect of depth ratio of soil movement on lateral displacement of pile groups: a)2x1, X/H_c = 0.6; b) 2x1, X/H_c = 0.9; c) 1x2, X/H_c = 0.6; d) 1x2, X/H_c = 0.9; e) 3x1, X/H_c = 0.6; f) 3x1, X/H_c = 0.9; g)1x3, X/H_c = 0.6; h) 1x3, X/Hc = 0.9.; i) 2x2, X/H_c = 0.6; j) 2x2, X/H_c = 0.9

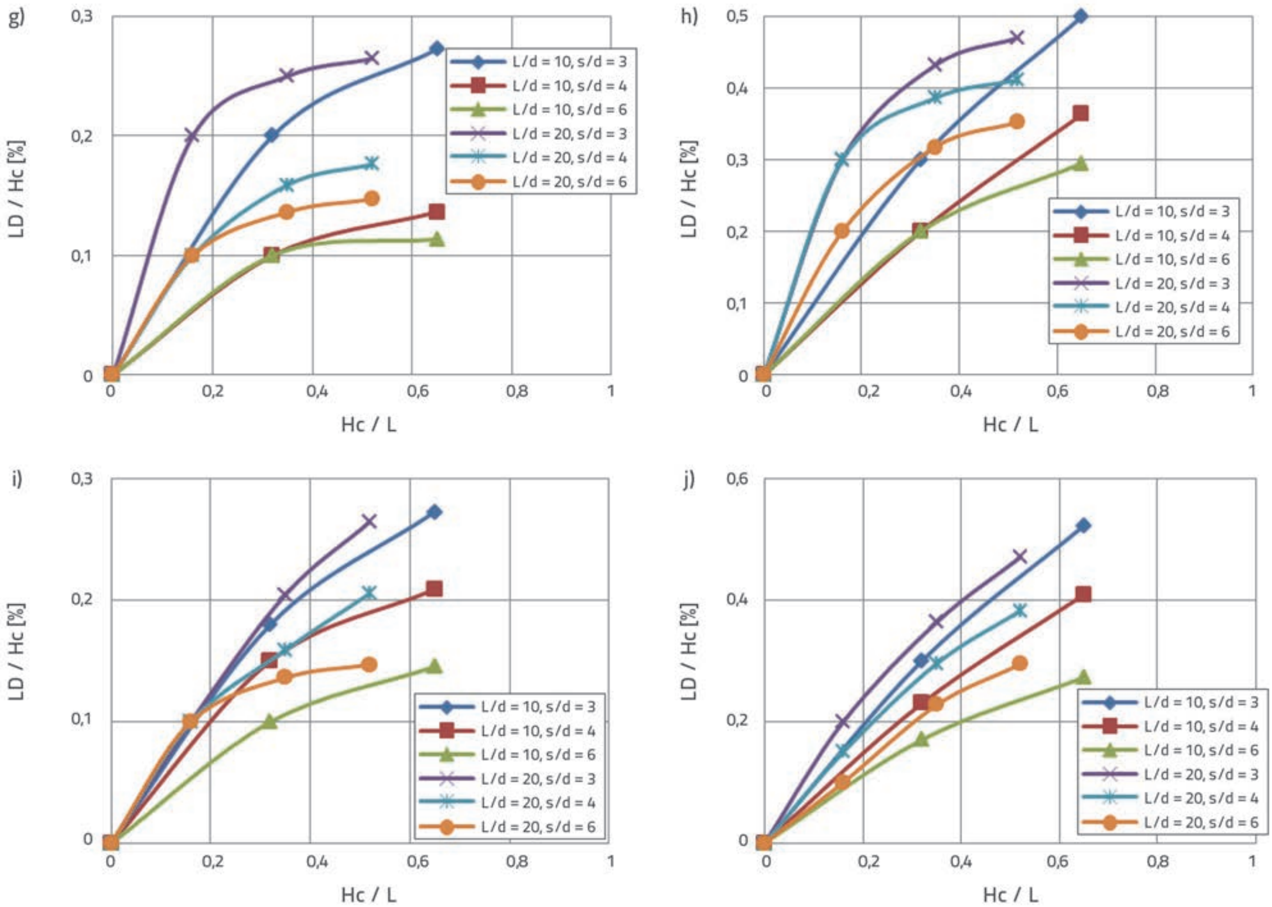

Figure 7. Effect of depth ratio of soil movement on lateral displacement of pile groups: a)2x1, X/H_c = 0.6; b) 2x1, X/H_c = 0.9; c) 1x2, X/H_c = 0.6; d) 1x2, X/H_c = 0.9; e) 3x1, X/H_c = 0.6; f) 3x1, X/H_c = 0.9; g)1x3, X/H_c = 0.6; h) 1x3, X/Hc = 0.9.; i) 2x2, X/H_c = 0.6; j) 2x2, X/H_c = 0.9 (resume picture)

configuration has a significant effect on pile behaviour. When a pile group (1 x 2, 1 x 3) is placed perpendicular to the retaining structure, the trailing piles provide additional resistance to the group [19]. Therefore, these piles groups experience a relatively smaller lateral displacement compared to the piles resting parallel to the retaining structure. The additional resistance developed in trailing piles is due to reduced load redistribution. Redistribution of load allows the trailing pile to induce additional stability to the pile group. However, the load does not redistribute in pile groups placed parallel to retaining wall (2 × 1, 3 × 1), as all piles are located at the same distance from the retaining wall and are subjected to the same load.

4.2.2. Effect of spacing

Figure 8 shows that nominal displacement of a pile group decreases with an increase in spacing. The resistance contributed from trailing piles increases with an increase in the spacing between piles and, consequently, it reduces lateral displacement of piles. In all pile groups, lateral displacement decreases significantly when spacing increases from 3d to 4d, which is attributed to the arching effect. Later on, an increase in the spacing from 4d to 6d has a smaller effect on pile displacement. This shows that the effect of spacing will decrease after a certain spacing, and every pile will behave like a single pile without being affected by neighbouring piles.

Though the group interaction effects exist for a spacing of 6d, the optimum group interaction effects can be achieved at the spacing of 4d. The spacing of 4d can be considered to achieve the maximum group interaction and arching effect [36]. Pan et al. [14], also found that the group effect exists even for a spacing of 5d. Figure 8 also shows that nominal displacement reduces significantly with an increase in spacing for pile groups of 1 × 2 and 1×3, as compared to pile groups of 2 × 1 and 3 × 1.

Abbas et al. [26] analysed a pile subjected to direct lateral loading. Similar to the present study, it was observed that lateral displacement reduces with an increase in the spacing and number of piles. The similarity in the observations by Abbas et al. [26] and those made in the present study indicates that the displacement of piles subjected to lateral loading induced from soil movement can exhibit behaviour similar to piles subjected to lateral force induced from any other source. However, the magnitude of displacement may depend on the source of soil movement induced.

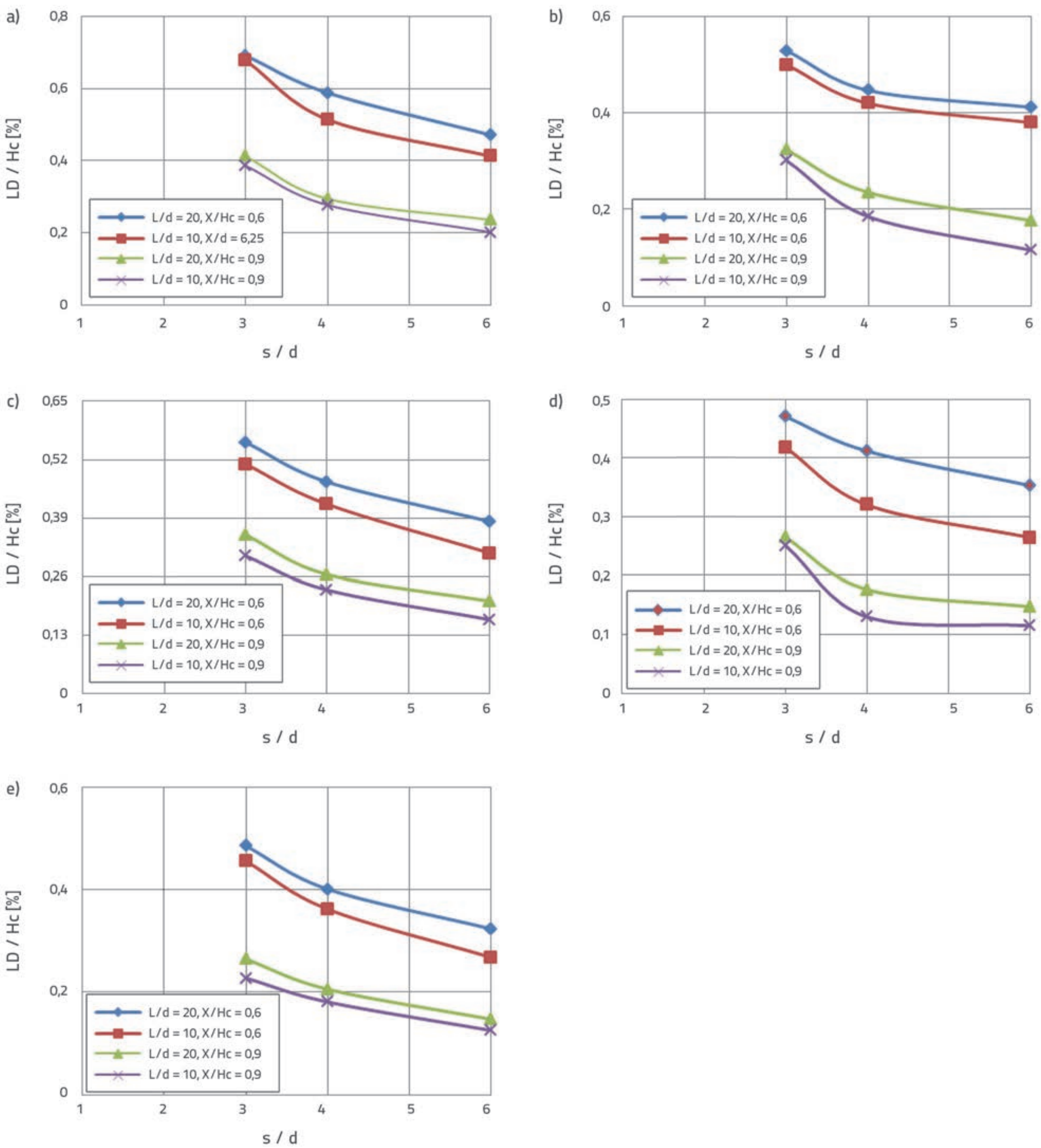

Figure 8. Effect of spacing on lateral displacement of pile groups: a) 2×1; b) 1×2; c) 3×1; d) 1×3; e) 2×2

4.2.3. Effect of embedment ratio of pile

The effect of embedment depth on lateral displacement of a pile group is shown in Figure 9. For a fixed spacing and depth ratio of soil movement, lateral displacement increases with an increase in embedment ratio of pile groups. Pile groups with lower embedment ratio behave like a rigid beam, but with an increase in embedment depth, piles exhibit behaviour of an elastic beam. Consequently, it may cause an increase in lateral displacement of piles. This might be due to two reasons:

a) the height of collapsed wall is normalized with respect to the length of pile and so, in longer piles, the smaller value of depth ratio of soil movement points to large depth of soil movement.
b) to higher working load in piles of greater length. A higher working load induces a relatively large magnitude of moment at pile cap even for small displacement of longer piles.

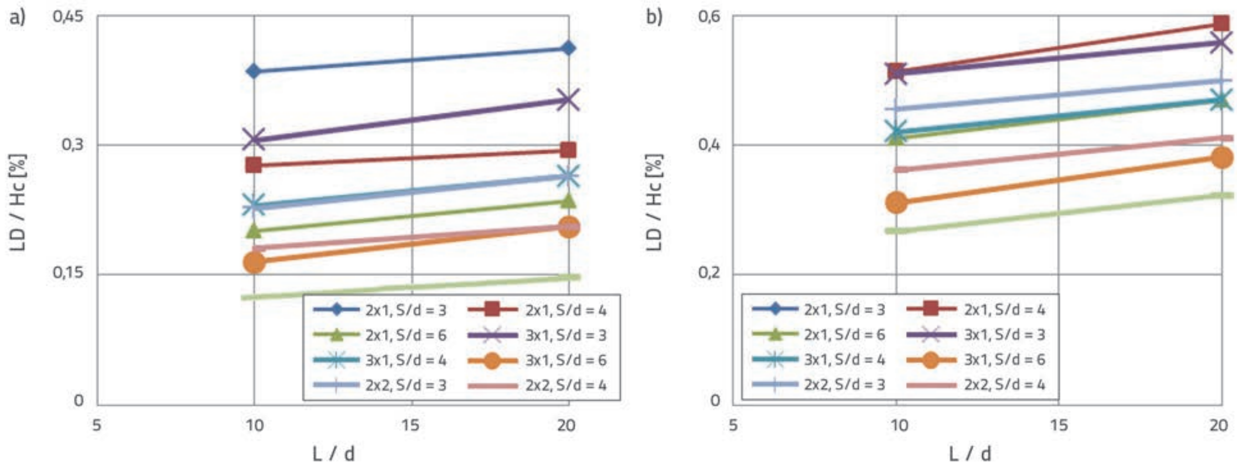

Figure 9. Effect of embedment ratio of piles: a) $X/H_c = 0.95$; b) $X/H_c = 0.60$

4.2.4. Effect of number of piles

Variation of lateral displacement of pile groups with the number of piles is shown in Figure 10. Lateral displacement of a pile group is always less than a single pile. Lateral displacement of pile groups decreases with an increase in the number of piles in the group for a particular spacing and embedment depth.

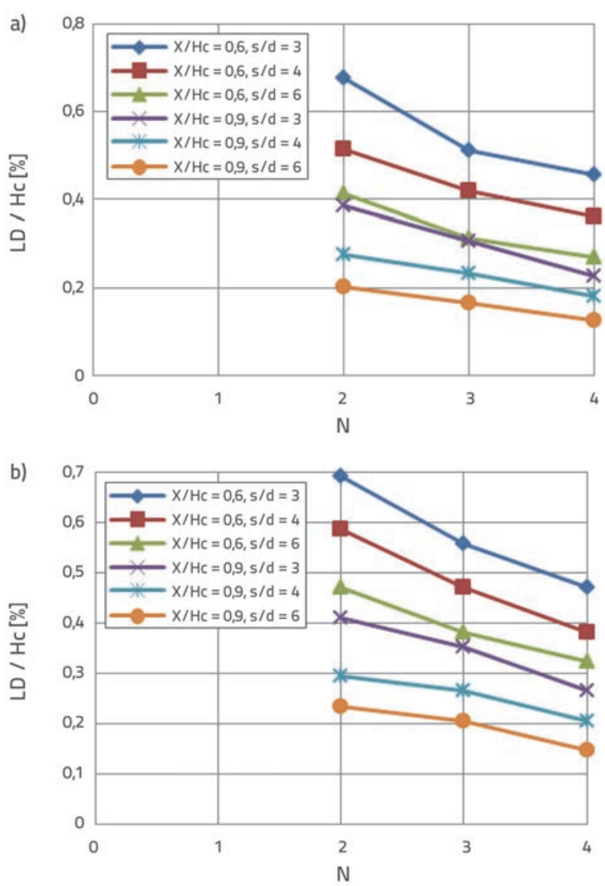

Figure 10. Effect of number of piles: a) L/d = 10; b) L/d = 20

This means that the group interaction effect has a positive impact on passive piles subjected to lateral soil movement. Shielding effect increases with an increase in the number of piles and imposes an additional resistance to soil movement, and consequently, it decreases lateral displacement of a pile group. The effect of the number of piles on lateral displacement depends on both the spacing and embedment length. At smaller spacing, the pressure bulbs overlap with each other with an increase in the number of piles, and the pile group behaves like a continuous wall. For larger spacing, the piles behave independently and soil movement through the piles remains largely unobstructed. Therefore, the rate of decrease in lateral displacement with the number of piles is relatively higher in small spacing (s/d = 3) compared to the pile group of large spacing (s/d = 4, 6). For a given pile spacing and pile group distance from retaining wall, it can be noted that the rate of decrease in lateral displacement increases with an increase in the length of piles (Figure 7).

4.2.5. Effect of distance between piles and retaining structure

Figure 11 shows lateral displacement of pile groups of embedment ratio 20. Lateral displacement decreases non-linearly with an increase in distance between piles and the retaining structure. A similar observation is made in the case of piles of embedment ratio 10. Both Leung et al. [19] and Liyanapathirana and Nishanthanmade [31] made a similar observation for a single pile under lateral soil movement.

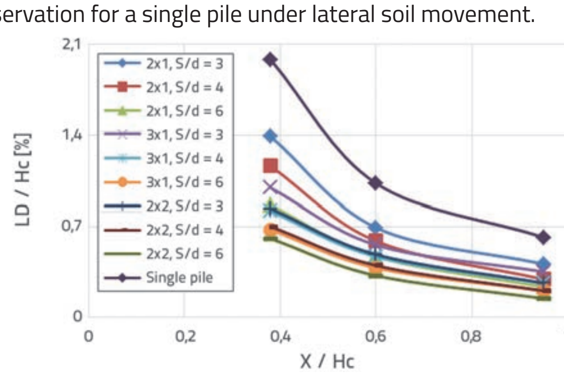

Figure 11. Effect of distance between piles and retaining structure

Displacement is large in the case of pile group of 2×1, with the spacing of three times the pile diameter. The effect of distance between piles and the retaining structure diminishes with an increase in the number of piles and spacing. The velocity of soil movement in the vicinity of a collapsed retaining wall is high, and it imparts a large force on piles near the retaining wall. The effect of the distance between piles and the retaining structure diminishes with an increase in the number of piles and spacing. Qiu and Grabe [35] stated that the pressure shielding effect is significantly influenced by the distance between piles and the retaining wall, while other factors, such as pile diameter and pile spacing, have a very nominal effect on it.
Figures 6-10 show that the nominal lateral displacement significantly depends on the distance between piles and the retaining wall, as compared to the number of piles, spacing, and embedment ratio of the pile. The strength of sand is stress dependent [37, 38]. Strength parameters of the foundation soil (sand) reduce significantly when the distance between the collapsed retaining structure and piles is small, as compared to the cases involving large distance. Therefore, the effect of distance is relatively more noticeable compared to other parameters.

5. Settlement of pile group

The abrupt collapse of the retaining wall induces settlement in the pile group. Similar to lateral displacement of the pile group, the settlement of pile groups depends on a number of parameters. Figure 12 shows settlement of piles group (2x1). Figures 12 a and b show variation of pile settlement (VD) with an increase in height of the collapsed retaining wall and pile spacing. Similar to lateral displacement, the pile settlement also increases with an increase in height of the collapsed retaining wall. Figure 12b shows that settlement increases with an increase in spacing. Similar observation was also made by Shan et al. [39, 40]. The rate of increase in settlement with spacing is relatively large in the case of a larger/higher collapsed retaining wall.

6. Conclusion

An abrupt collapse of a retaining wall has a severe effect on pile performance. The normalized displacement of a pile group increases with an increase in height of a collapsed retaining structure. Piles placed perpendicular to a retaining structure display small displacement as compared to parallel placed piles due to a reduced load redistribution. Lateral displacement of piles decreased with the application of load on piles. Furthermore, it decreased with an increase in the spacing and number of piles in a pile group. The rate of decrease in lateral displacement with the number of piles is relatively higher in the case of small spacing and longer piles. However, the normalized displacement increased with an increase in the embedment ratio of the pile and pile group. The pile group resting near the collapsing retaining structure exhibits a large displacement. Lateral displacement is significantly reduced as the distance is increased between the retaining structure and piles. In the presented study, the embedment ratio was changed by changing the length of the pile. The settlement of pile increases with the critical height of the retaining structure and the spacing of the pile group. In further studies, the diameter of the pile can be changed to determine its effect on the behaviour of piles subjected to soil movement. A large range of spacing, number of piles and sand density can also be used in future studies. Special attention should be paid to the settlement of pile group due to abrupt failure of the retaining structure.

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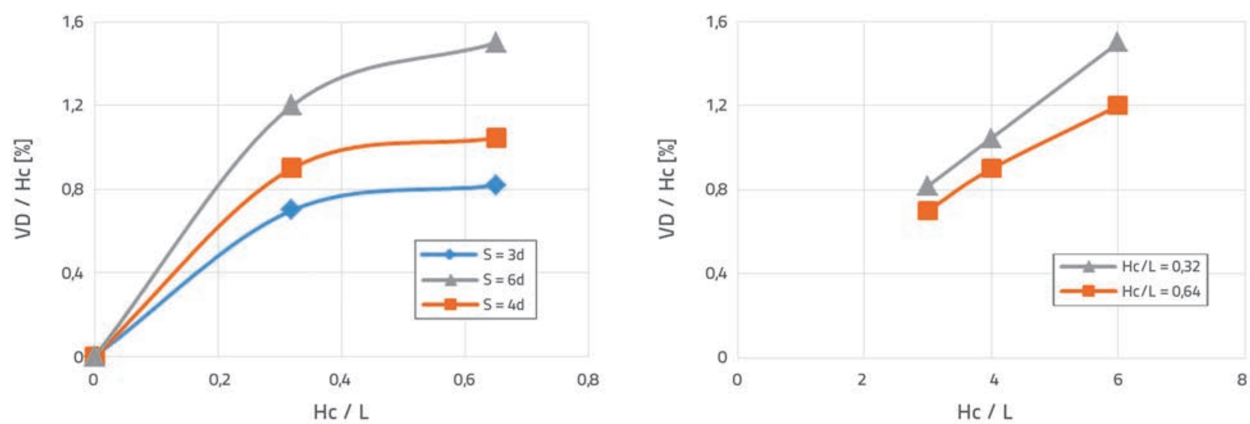

Figure 12. Variation in piles settlement: a) with an increase in Hc; b) with an increase in spacing.

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