Forensic analysis of failure of shoring piles

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ABSTRACT: Shoring piles had been provided to support the sides of a deep excavation carried out for the construction of a shopping mall having three basements. A section of the shoring piles failed suddenly when the lowest basement had already been constructed and partial backfilling had been carried out. As the failure occurred when the loads and moments on the shoring piles were lower than what they had earlier been subjected to, the cause/s for the sudden failure were not apparent and nor readily discernable. Therefore, forensic analysis of the failure of the shoring piles was carried out by collecting various data which included construction records, collation of eyewitness accounts and study of post failure conditions. Back analysis of the shoring pile system was carried out by formulation of an alternate method of analysis of the shoring piles. Finally, a hypothesis regarding the failure mechanism was developed and tested for possible inconformity.

1 INTRODUCTON

A shopping mall had been under construction at Amritsar city in the state of Punjab in India. The proposed structure for the mall consisted of three basements, a ground floor and four upper floors to be constructed in a plot measuring approximately 85 x 95m in size. Excavations for the basements had earlier been carried out down to the required depth of about 13m below the existing ground level. The sides of the excavations had been supported by reinforced cement concrete circular bored cast-in-situ shoring piles, in a pattern as shown in fig.1. Wire mesh and guniting had been provided as facing to the shoring piles to retain the soil between the piles. This method of side support had been adopted on three sides of the excavation as shown in fig.2.

The excavations and the construction of the lower basements proceeded smoothly without any major difficulties till the time of the laying of the roof of the second basement had been reached. The soil backfilling along the outer periphery of the structure had been carried out in stages as the construction of the basements progressed and had reached above the top level of the lowest basement. On the 25th of May 2007, a section of the shoring piles located on the Northern side of the plot failed suddenly in the middle of the night. Fortunately, as the failure occurred in the night when very few workers were at the construction site, no casualties or injuries were reported.

The fact that the failure did not occur when the depth of excavation had been the maximum but occurred when partial backfilling had already been carried out is notable. This implies that the failure occurred when the loads and moments on the shoring piles were lower than what they had earlier been subjected to. Therefore, the cause/s for the sudden failure were not apparent and nor readily discernable. Hence, a forensic analysis was carried out to assess the probable cause/s for the failure.

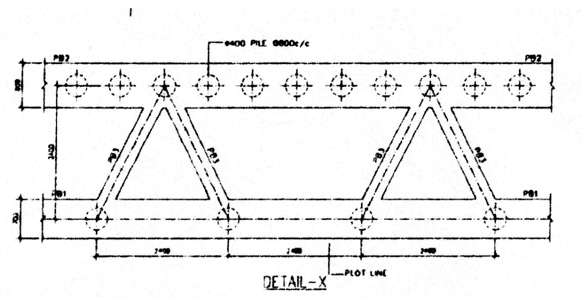

Fig. 1 Pattern of shoring piles

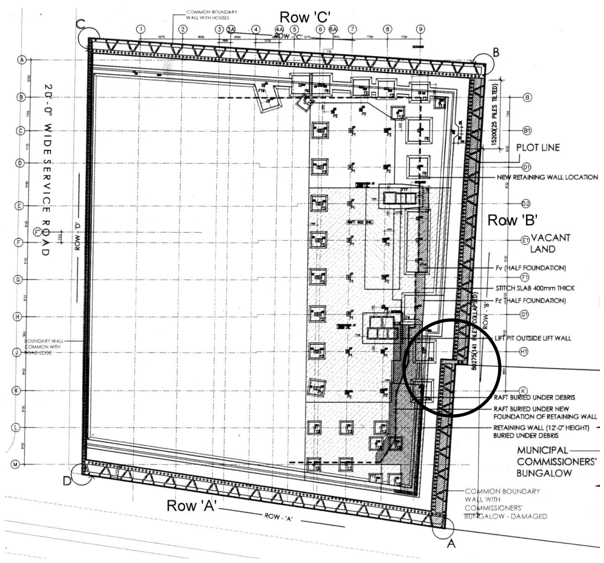

Fig. 2 Schematic site layout

2 DATA COLLECTION

2.1 *Shoring pile system*

The shoring piles had been provided in a pattern as shown in fig.1. As per discussions held with the structural designers for the project, the front / facing row of shoring piles were provided for retaining the soil while the rear row of piles, lesser in number (i.e. one rear row pile for every 3 front row piles) were provided as anchors for the front row of piles with the anchoring ties provided at the top end of the piles in a triangular pattern as seen in the above figure. Capping beams had also been provided along the top of both the front and rear row of piles

The shoring piles were 400mm diameter reinforced cement concrete bored cast-in-situ piles provided down to a depth of 18.5m below the existing ground level. The spacing of the front row piles was 0.8m while that of the rear row piles was 2.4m. The spacing between the two rows of piles was 2.4m.

The reinforcement provided in the piles consisted of 6 bars of 16mm diameter for the full length of the piles with circular ring stirrups of 8mm diameter provided at 200mm intervals.

The shoring piles were constructed by two different contractors who used different methods of progressing the pile bore. While one piling contractor used the traditional drilling mud circular (DMC) method with shell/bailer for progressing the pile bore, the other piling contractor used the auger method for progressing the pile bores.

A sloping soil surface had always been maintained between the basement line and the shoring piles so that the effective freeboard for the shoring piles was always less than the depth of excavation at the basement line.

2.2 *Soil conditions*

The soil conditions at the site of the project as indicated by the detailed soil investigation report for the project are as given below.

The soil consists of a top about 3m layer of silty sand overlying poorly graded fine sandy soil down to the termination depth of the boreholes of 30m below the ground level.

The soil is in a medium dense state throughout the 30m depth investigated with the N-values on average being in the range of about 20.

Ground water table exists at a depth of about 15m below ground level, which is deeper than the maximum depth of excavation.

2.3 *Information from Site Personnel*

The information deduced from the interviews of the site personnel present at the time of the collapse are given below:

1. The collapse occurred in the night between about 20:00 hrs and 21:00 hrs IST.
2. The collapse had been sudden and without warning and a loud breaking sort of sound had been heard at the time of the collapse.
3. The collapse event occurred within a few minutes. Fortunately, workers who had been working in that area had retired for refreshments when the collapse occurred.
4. No signs of distress had been observed in the shoring piles prior to the collapse such as bending/displacement of piles and/or bending in the capping beams of the shoring pile system.
5. The collapse was accompanied by a lot of dust flying into the air.
6. There had been no sign of slush of any form in the collapsed area.

2.4 *Information from photographs*

Photograph showing the shoring piles prior to the failure is given in fig. 3, This photograph had apparently been taken prior to the guniting of the face of the shoring pile system. The photograph also shows clearly the sloping soil surface between the shoring piles and basement line.

Although photographs had apparently been taken immediately after the failure event, these were not made available. However, some photographs taken a few weeks after the event, were made available and are shown in figs. 4 to 6. These photographs show different views of the area of the collapsed shoring piles thus giving an overview of the status of the site post failure.

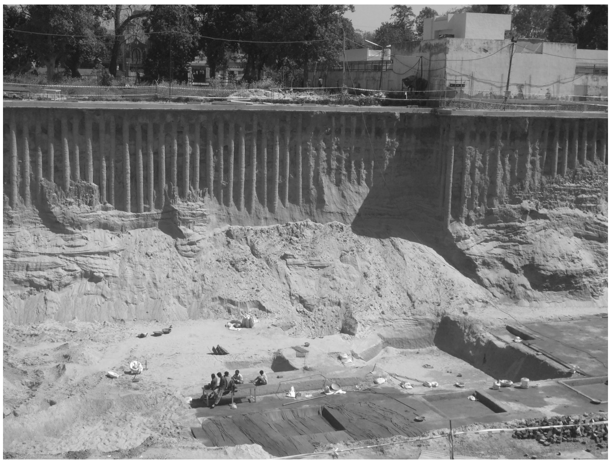

Fig. 3 Shoring piles prior to failure

b. The failure surface in the soil behind the line of shoring piles is only a few metres distance from the line of shoring piles and is almost vertical in the upper portion as seen from the photograph in fig. 4.
c. Other views of the collapsed area very clearly show the bent and broken piles in photographs in figs. 5 & 6. The orientation of the bent piles indicates that the bent portion of the piles is only a few metres in length.
d. The guniting adopted in the upper part and the sand bags provided in the lower part for preventing the soil behind the shoring piles from flowing out can be seen in the background in the photograph in fig. 4.

Fig. 4 Post failure conditions

Fig. 6 Another view of post failure conditions

Fig. 5 Front view of shoring piles post failure

The information obtained from these photographs are as follows:

a. The piles are observed to have bent forward as seen from the photograph in fig. 4.

2.5 *Miscellaneous Information*

Additional information collected though not directly related to the collapse but of importance in determining the cause/s of the collapse are given below:

The shoring piles along the site boundary in which the collapse occurred (i.e. row B; marked by shading in fig. 2) had been constructed by drilling the pile bores using the traditional DMC (i.e. drilling mud circulation) method and temporary liner/casing of about 6 to 8m length had been used during the drilling.

Heavy rains had occurred a few days prior to the collapse.

The depth of excavation had earlier been significantly larger when the raft foundation had been cast in this area and also when the retaining wall of the lowest basement had been constructed. Thereafter, backfilling had been carried out between the shoring piles and the retaining wall thus reducing the depth of the excavation along this site boundary. Hence, the collapse occurred when the depth of excavation in front of the shoring piles had been significantly lesser than earlier.

3 POSSIBLE MODES OF FAILURE

To assess the probable cause/s of the collapse, the various primary modes of failure of any soil retention system have to be first taken into account. The various primary modes of failure of a soil retention system are discussed below.

Failure by overturning
In this mode of failure, as the name suggests, the retention system overturns/tilts towards the excavated side due to the active pressures on the retained soil side exceeding the passive resistance from the soil on the excavated side.

Failure by sliding
In this mode of failure, as the name suggests, the retention system slides generally due to a deep seated circular failure surface by which the soil on the excavated side moves out and the bottom portion of the retention system moves along with the same.

Structural failure
In this mode of failure, the retention system undergoes structural failure by bending and/or shear. In other words, capacity of the structural elements of the retention system to carry the imposed bending moments and/or shear forces caused by the retained soil is exceeded. The structural failure can manifest either in the form of distress (i.e. excessive deformations of the retention structure) if the structure is designed and constructed properly or in the form of complete and sudden failure (i.e. breakage of the retention structure) if the structure is designed and/or constructed improperly.

4 STATEMENT OF FACTS

In assessing the cause/s of the failure, the facts of the event should first be clearly considered. The facts are:

1. The collapse was sudden and without any warning signs whatsoever in the form of observed bending of piles and/or of the top capping beams. This is typically indicative of brittle failure, the type of failure associated with concrete.
2. The observed collapse is indicated to be in the form of bending and consequent breaking of the shoring piles and not by overturning.
3. The length of the bent portion of the shoring piles is approximately 6 to 8m as indicated by the distance from the line of the shoring piles to the outer limits of the bent piles.
4. The observed failure surface in the soil behind the shoring piles is similar to that normally observed in relatively dry silty sand soil in a medium dense state, in that the failure surface is vertical in the upper part and is only a few metres behind the line of shoring piles. Had the soil been saturated, the failure surface is likely to have been a proper slope with evidence of flow of the soil having taken place.
5. The construction staff at the site have indicated that there had been a lot of dust immediately following the collapse and that there had been no sign of slush indicating that water and the consequent hydrostatic pressure caused by it had no role to play in the collapse.
6. The collapse occurred at a time when the depth of excavation in front of the shoring piles was significantly lesser than the full depth as backfilling had already been carried out after the construction of the lowest basement retaining wall.
7. The shoring piles had worked satisfactorily without any signs of distress when full depth of excavation had been carried out earlier.
8. The remaining intact shoring piles have continued to work satisfactorily even under higher surcharge loads on the retained side as is the case of the shoring piles along row ‘C’ in fig. 2. As seen in the background in fig. 4, this row of piles are carrying surcharge loads from single and double storied buildings located adjacent to the site boundary.

5 INFERENCES FROM FACTS

Taking into account the above facts, the following inferences can be made:

a. The mode of failure of the shoring piles has been by structural failure of the shoring piles in that the upper portions of the shoring piles have broken and bent forward.
b. The sudden failure by bending of the piles indicates that the strength of the concrete in the failed section had been poor as otherwise the failure should have been gradual with clear signs of distress like that of an underreinforced section.
c. Water had not been present in the soil behind the shoring piles and therefore, hydrostatic pressure that could have been caused by the presence of water had also not been present. Hence, water had no role to play in the collapse. This is indicated by the facts stated earlier.
d. Failure has not occurred when the full depth of excavation had been carried out but has oc-

curred when the depth of excavation had been significantly lesser. This is borne out by the facts given earlier.

e. The remaining intact shoring piles have continued to perform satisfactorily without any signs of distress despite some of these shoring piles being subjected to surcharge loads on the retained side.

6 BACK ANALYSIS OF SHORING PILE SYSTEM

As the mode of failure is inferred to be structural failure of the shoring piles, the structural design of the shoring piles have to be checked. Unfortunately, the structural design calculations for the shoring were not made available. Due to unavailability of the structural design calculations for the shoring piles, back analysis has to be carried out based on the available structural drawings.

In any case, the fact that majority of the shoring piles are intact and performing satisfactorily and in particular the fact that many of these intact shoring piles are subjected to surcharge loads on the retained side, clearly indicates the shoring piles are structurally adequate. However, back analysis is imperative to demonstrate that the shoring piles are structurally adequate.

If the shoring pile system were to be analysed as an earth retention system consisting only of the single front row of shoring piles and the role of the rear row of piles, if any, is neglected, the system would at the outset be considered to be highly inadequate.

On the other hand, the proximity of the rear row of shoring piles to the front row of shoring piles would imply that the presumed anchoring effect of the rear row of shoring piles is unlikely. This is because the lateral forces/stresses applied on the soil wedged between the two rows of piles, by the rear row of piles, would to a large extent be transferred as lateral forces/stresses onto the front row piles.

However, considering the kind of wedging action of the soil between the two rows of piles as discussed above, the two rows of piles along with the wedged soil can be considered to act as a single body and is hence, analysed as such. In such an analysis, the front row of shoring piles are considered to be only under compression with tension being carried by the rear row of piles. In effect, the shoring pile system behaves in a manner similar to a steel truss system with tension and compression members and the role of the braces between the tension and compression members being played by the wedged soil in the shoring pile system.

Hence, the analysis becomes straightforward in that equilibrium of moments can be taken about point of intersection between the formation level and the front row of shoring piles, marked as point A in fig.7, which then leads to the equation given below:

$$FS = \frac{\left(\frac{1}{2}\cdot\gamma\cdot H\cdot K_a\cdot\frac{H}{3}\right)}{\left(W\cdot\frac{S}{2}+T\cdot S\right)}$$

(1)

where g = unit weight of soil; H = depth of excavation; Ka = coefficient of lateral active earth pressure; W weight of the soil mass wedged between the front and rear rows of shoring piles; S = spacing between the two rows of shoring piles; and T is tensile capacity of the shoring pile.

By carrying out this analysis for the configuration of the shoring pile system adopted in the present case and taking into account the reinforced concrete section provided in the shoring piles, the factor of safety against failure even under the maximum depth of excavation of about 9m, works out to be about 1.45.

Hence, the possibility of the failure having occurred due to structural inadequacy of the shoring pile system can be more or less ruled out.

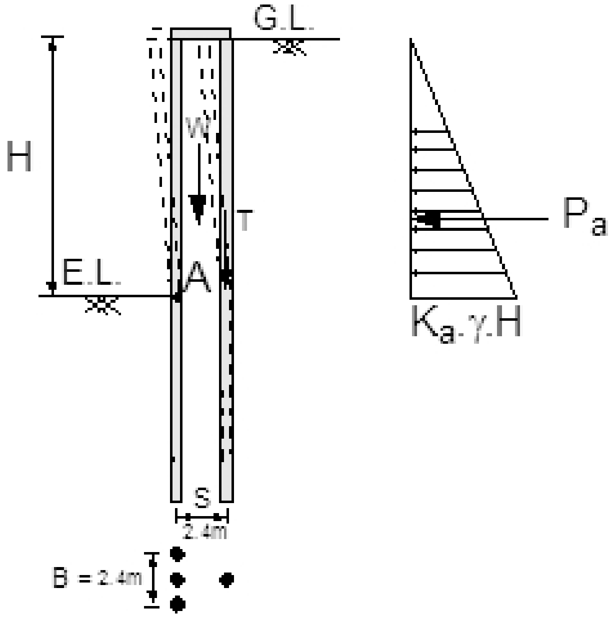

Fig. 7 Analysis of shoring pile system

7 ASSESSMENT OF PROBABLE CAUSE/S OF FAILURE

In view of the back analysis having shown that the shoring pile is structurally adequate, the structural failure of the shoring pile system can only occur due to poor concrete. The facts indicate that primarily the failure has occurred due to the presence of concrete of poor quality between 6m and 8m depths. The significant point to note is that a few of the piles adjacent to each other in a small section have failed or in other words given way and thereafter the collapse progressed towards both sides as high loads from the failed section gets transferred to the adjacent sections of the shoring pile system.

Notably, the centre point of the collapsed portion of the shoring piles more or less lies at the break/shift in the continuous line of shoring pile system as indicated by the circle marked in fig. 1. This break/shift in the continuous line of the shoring pile system is critical in that any defect in the construction at this location can prevent the proper functioning of the shoring pile system as a two-dimensional system and instead make the shoring piles at this location act as free standing piles and consequently, cause a reduction in factor of safety against structural failure eventually leading to the structural failure of the piles at this location.

In view of the above, the indications are that two causative factors have occurred simultaneously in that:

1. Poor quality concrete had probably been present between 6m and 8m depths, which is the critical section for the depth of excavation at the time the collapse
2. Poor quality concrete in the shoring piles had probably been present at the location of the shift/break in the line of the shoring pile system.

When the shear forces and bending moments generated in a shoring system are considered, the locations of the maximum shear force and the maximum bending moment in the shoring system are generally spaced within a height of about 10 to 20% of the total height of the shoring system and just a few metres below the top surface of the soil on the excavated side of the shoring system as seen in fig.4. Hence, as and when the depth of excavation reached such a level that the above mentioned section of the shoring system coincided with the section of the shoring system having poor quality concrete, the failure of the shoring pile system would have been triggered.

At the present site, the shoring pile system had worked satisfactorily even with maximum required depth of excavation. This is because at the maximum required depth of excavation, the locations of the maximum shear force and maximum bending moment in the shoring piles would have been deeper than 8m. After the backfilling had been carried out after completion of the lowest basement, the above locations would have fallen within the depths of 6m to 8m wherein the poor concrete had probably been present thus triggering the failure of the piles and the consequent collapse.

The presence of poor concrete in the section of shoring piles between 6 and 8m depths can be on account of the method adopted for the construction of the shoring piles. The pile bores had been drilled by the drilling mud circulation method with a temporary liner/casing only within the top approximately 6m length of the pile and thereafter tremie concreting had been carried out. Improper methods adopted in the withdrawal of the temporary casing while concreting the piles, can lead to poor quality of concrete near the bottom end of the temporary casing depth that is about 6m depth.

8 CONCLUSIONS

The above analysis of the possible cause/s of the failure of the shoring pile system have shown that:

a. The shoring pile system has most likely undergone structural failure.
b. The structural failure has most likely occurred due to two causative factors having occurred simultaneously:
   i. Presence of poor quality concrete between 6m and 8m depths, which is the critical section for the depth of excavation at the time of the collapse.
   ii. Presence of the poor quality concrete in the shoring piles at the location of the shift/break in the line of the shoring pile system.

REFERENCES

Macnab A. (2002), Earth retention systems, McGraw Hill, New York

Puller, M. (1996), Deep excavations – a practical manual, Thomas Telford, London