PIPING FAILURE IN SUBWAY CONSTRUCTION DUE TO INTERNAL EROSION OF SILTY SAND

Kenji ISHIHARA[1] and Wei F. LEE[2]

[1]Member of ISSMGE, Professor, Dept. of Research and Development Initiative, Chuo University
(1-11-5, Kudan-kita, Chiyoda-ku, Tokyo 102-8220. Japan)
E-mail:ke-ishi@po.iijnet.or.jp
[2]Member of ISSMGE, Associate Research Professor, Office of Research and Development,
National Taiwan University of Science and Technology
(Sec. 4, Office of Research and Development, No. 43, Keelung Rd., Taipei 10607. Taiwan,)
E-mail: weilee@mail.ntust.edu.tw

The incentive for the present study was instigated by the large-scale cave-in at the site of subway construction in Kaohsiung, Taiwan, which occurred as a result of piping in a silty sand deposit at the bottom of the excavation. In view of the circumstances that, nowhere has the piping been observed more conspicuously than in the deposits in Kaohsiung, particular nature of the local silt was suspected to have been one of the causes leading to the occurrence of the piping. The results of pinhole tests and specific surface measurements conducted for forensic investigation revealed peculiar characteristics of the local silt which is highly vulnerable to internal erosion subjected to seepage flow. Thus, the importance of exploring unknown nature of local soils was recognized as an important lesson to be paid attention particularly when construction projects are to be executed in areas of few experiences of deep excavations.

Key Words : *Piping, Subway, Internal erosion, Silt, Pinhole test*

1. OUTLINE OF THE INCIDENCE

Subway construction had been underway in east-west direction in the central part of Kaohsiung. Upon finishing the tunnel construction by the method of earth-balanced shield, the corridor connecting the two tunnels (up-line and down-line) was constructed by means of what is called the NATM method involving open excavation with the help of steel -framed support and injection. Then, a vertical shaft 3.3m in diameter was excavated to provide a sump for water collection in the middle of the corridor in open dry conditions with the support of the H-shaped circular beams. When the shaft excavation reached a level 4.95m from the floor of the corridor, a chunk of wet soil tumbled out from the southern wall of the shaft at the bottom. The small collapse was followed by steadily increased outflow of mud water. The amount of water increased minute after minute. This breakage further led to undermining the already built-up tunnels, accompanied by an inflow of soil and water from the rips opened on the ceiling at the junctions between the shield segments. This breakage culminated eventually in a large scale collapse of the tunnel structure involving formation of two cave-ins on the ground surface.

2. DESCRIPTION OF THE SITE CONDITIONS

The feature of the cave-in on the ground surface is displayed in Fig. 1. A bird-eye view over the cave-in is displayed in Fig. 2. The plan and side view of the tunnel are shown in Fig. 3. It is to be noted that there was an underground roadway called Chung Cheng underpath just above the subway tunnel. The dual tunnels were constructed by the tunnel boring machine (TBM) which can advance by rotating a large steel disk equipped with cutting blade, while the cutting face is balanced by the mud pressure.

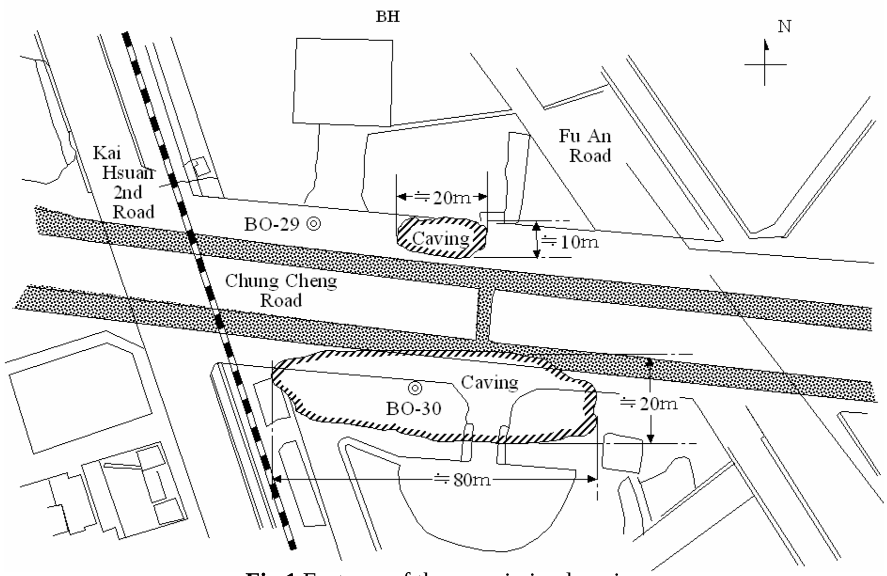


Fig.1 Features of the cave-in in plan view.

Fig.2 A bird-eye views over the cave-in in Kaohsiung.

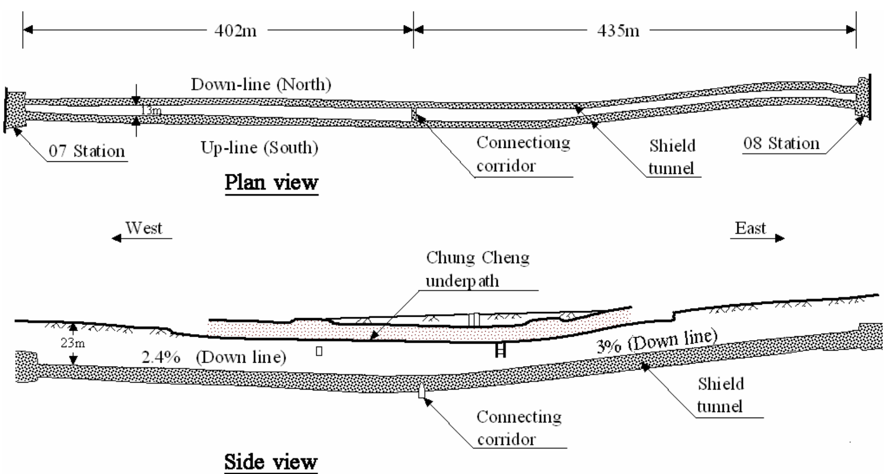


Fig.3 Plan and side view of the tunnel.

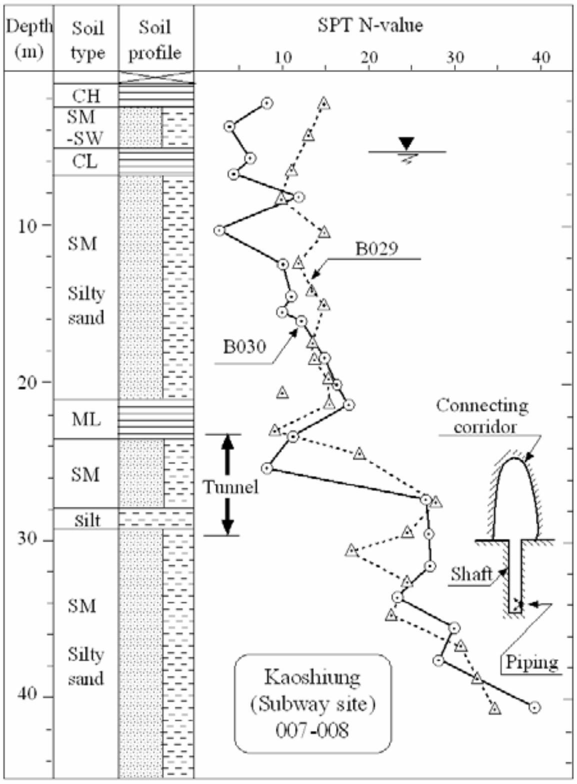


Fig.4 Soil profile at the site of collapse.

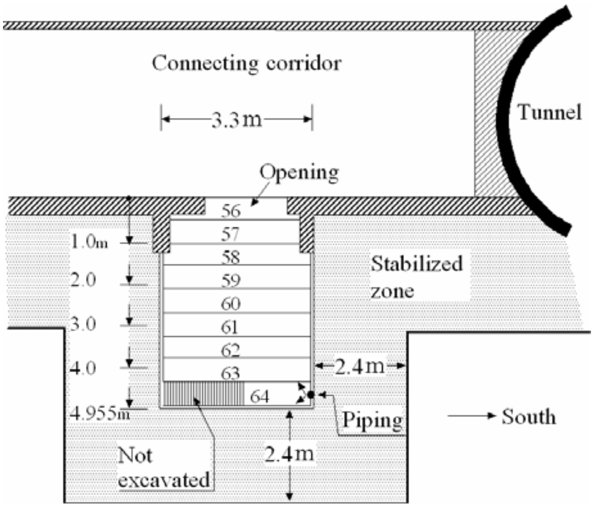


Fig.5 Details of the excavation for the sump and initiation of piping.

The soil profiles at the locations BO29 and BO30 in Fig. 2 are indicated in Fig. 4, where it can be seen that the deposits are comprised predominantly of silty sand with occasional layers of low-plasticity clay (CL) to a depth of 40m. The blow count, N-value, in the standard penetration test is shown to increase with depth and to have a value of 20 to 30 at the depth where the sump for water collection was excavated.

The section of the ground where the corridor was to be installed had been stabilized by means of the jet grouting, where milky cement mortar is jetted out horizontally into the ground, resulting in the formation of solidified columns of soils with a diameter of 30m. Each column was installed so as to have mutual overlapping of 60cm and to produce a huge stabilized massive zone 8.73m by 25.487m in plan which was considered strong and competent enough to permit excavation of the connecting corridor and the sump to be carried out in dry open conditions without any distress.

On December 4, 2005, the piping occurred at 3:30p.m. at the very last stage of excavation of the sump. A block of silty sand was detached from the south wall at the bottom of the excavation which is located at a depth of 35m from the ground surface. The circumstance at this time at the bottom of the sump excavation is illustrated in details in Fig. 5.

A sequence of the events after triggering the piping which are likely to have occurred is illustrated in the cross sections in Fig. 6. The blackish mud water continued to come out in the sump with increasing volume. Two men at work at the bottom strove in vein to clog the hole by dumping sand bags from the corridor. About two hours later, the workmen closed the entrance to the sump by placing a steel lid and several bars for its support (Fig. 6(a)).

It is believed that the mud water flowed into the sump from the bottom through a single hole probably with a diameter of about 30cm. This assumption would hold true in the light of the fact that the zone stabilized by the jet grouting could not so easily broken down in the horizontal direction, and a weak zone might have existed in the vertical direction.

About a few hours after the initial collapse, engineers at spot heard squeaking sounds of breaks at segment joints of the tunnel on the south, accompanied by mud water cascading from the ripped joints of segments at the ceiling. It appears likely that because of the underscoring of the bottom portion, the stabilized zone subsided together with the tunnel body, resulting in the stepwise settlement in the longitudinal directions illustrated in Fig. 6(a).

Around 10:20p.m., the fall-off of the soil above the ceiling had spread upwards and, assisted by the slipping along the vertical wall of the motorway structure, soil mass fell down into the tunnel. This resulted in creation of a large cave-in on the ground surface on the south side as illustrated in Fig. 6(b). At this time, two mains 60cm and 30cm in diameter for water supply were broken releasing a large amount of water for a prolonged time. This breakage of the buried pipes appears to have transferred the collapsed soil deposits into more flowable debris.

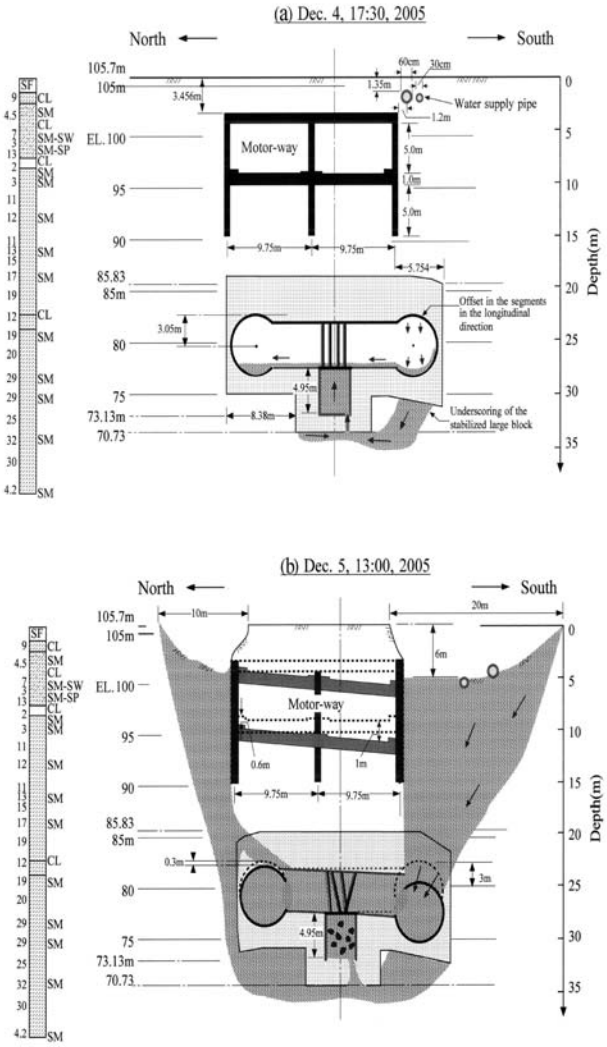


Fig.6 A sequence of likely scenario for progressing the piping failure.

3. INVESTIGATIONS INTO CAUSES OF FAILURE

After the collapse, the Committee of Investigation was organized by the Kaohsiung Mass Transit Authority. There were several points agreed upon by the Committee which could be summed up as follows.

(1) It was obvious from the testimony of the two men at work that the phenomenon of piping was a generic cause for triggering the collapse.

(2) The reasons why the piping was initiated were conceived variously. One of them was existence of seepage-prone weak zones resulting from imperfect overlapping in the arrangement of the soil-cement columns created by the jet-grouting method.

(3) The hydraulic pressure at the depth of 34m where the piping was initiated was estimated as being about 300kPa and the length of conceivable shortest path for seepage was 2.4m as counted from the bottom level of the stabilized zone. Thus, the hydraulic gradient at the time of the piping is estimated as having been of the order of i=30m/2.4m=12.5 which was fairly high.

(4) Thus, it is expected that the critical hydraulic gradient for unstable seepage was about 12.5, although the reason for this to occur remained unidentified. It was also suspected rather strongly that the silty sand in the area of Kaohsiung might be possessed of a peculiar characteristic which is vastly prone to internal erosion as compared to soil deposits existing in other parts of the world. Thus, once the piping develops, the deposit is least self-healing and tends to become easily unstable.

4. PRONENESS OF LOCAL SOILS TO INTERNAL EROSION

There have been several small collapses reported in other sections of subway construction in Kaohsiung. In fact, it was a concern among geotechnical engineers working there that the fines in sand deposits in Kaohsiung must be highly non-plastic and easy to flow. Thus, one of the key issues for forensic diagnosis was focussed on the extremely flowable nature of silts in Kaohsiung area which has not ever been addressed elsewhere.

As is well-known, the susceptibility of a given silty sand to internal erosion can be understood from two points of views, that is, generic reason and durability or resistivity.

(1) If an aggregate of a soil is comprised of two major groups each having significantly different particle sizes, the grains with smaller size can move easily through pores of the matrix formed by larger particles. Thus, if such a soil with a gap grading is subjected to seepage flow, the smaller particles can be easily detached and washed away. This is the seminal concept underlying the criterion for the design of filters in rockfill dams.

(2) The condition as to whether or not a given soil actually suffers the piping collapse is expressed in terms of the critical hydraulic gradient, that is, the resistivity. In fact, the experiments by Skempton and Brogan (1994) showed that the critical hydraulic gradient, ic, for the occurrence of piping in gap-graded sand-gravel mixture could be as low as

0.2-0.3 as against i=0.9-1.0 for clean sands. This would hold true for soils with the range of particle size coarser than the silty sand in Kaohsiung. To the author's knowledge, there appears to be no study ever performed to clarify the vulnerability to piping or internal erosion for silty sands or sandy silts subjected to the seepage flow. Thus, this issue was taken up as a new problem area deserving further scrutiny to identify causes of the collapse in deep-seated excavation.

5. LABORATORY TESTS ON INTERNAL EROSION

With respect to the piping or erosion, there would be three types of categories to be distinguished depending upon the range of grain size of soil materials in question. These are shown in a graphical form in Fig. 7. The segregation piping has been the target of extensive studies in the past in association with the filter criteria for the design of rock fill dams. There are many studies reported in this context such as those by Terzaghi (1939), Kenny-Lau (1986), Skempton-Brogan (1994) and Sherad (1979).

Erosion in clay-silt materials has been investigated by Sherad (1979) in response to the problem emerging from occasional failure of low-height earth dams which occurred upon water filling in Australia and U.S. The grain sizes associated with erosion or gully formation has been known to lie in the range indicated in Fig. 7. It is known that dispersive nature of clayey soils is a dominant factor for inducing gulley or erosion tunnels in the clay fills. Tests for chemical analysis and pinhole tests were suggested as means to identify the dispersive nature of the fine-grained soils.

The outcome of the grain-size analyses for the silty sand at Kaohsiung has shown that the soil there belongs neither to the broadly graded gravelly sands for the segregation piping nor to the dispersive clay related to the erosion or gulley formation. In fact, the grain size in Kaohsiung soil lies midway in the range of silt and sand, as indicated in Fig. 7, which is coarser than the dispersive clay and finer than the soils related with segregation piping. Thus, the collapse of the silty sand in the subway construction in Kaohsiung was considered to have posed a new challenge and addressed a novel problem area. The solution for this is not yet settled, but performing some tests was regarded as a useful attempt to shed some light on this problem. In this context, a set of pinhole tests and measurements of specific surface were performed as described below.

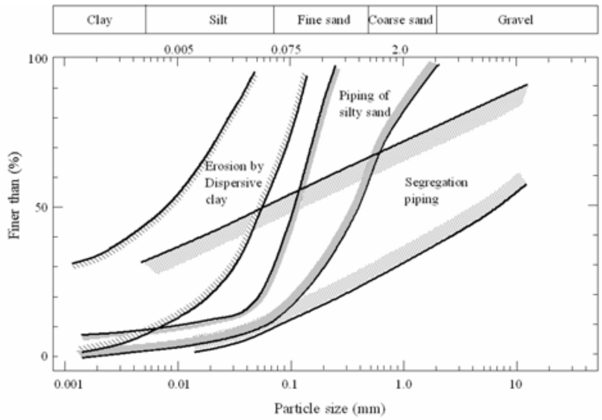


Fig.7 Three groups of soils in terms of grain size range associated with erosion and seepage instability.

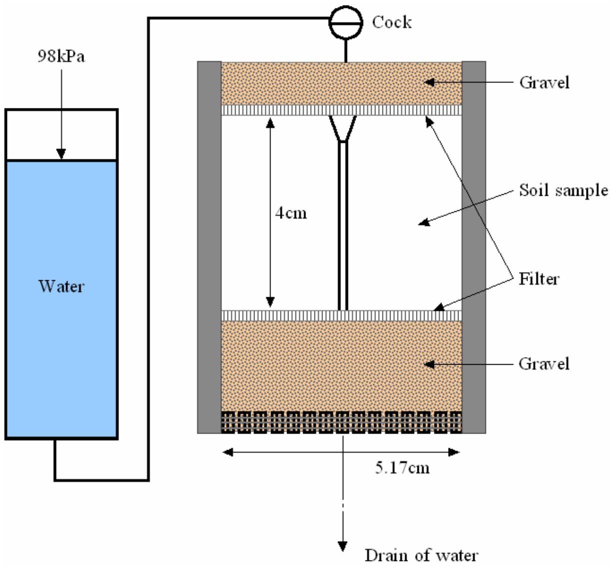


Fig. 8 Layout the pinhole test.

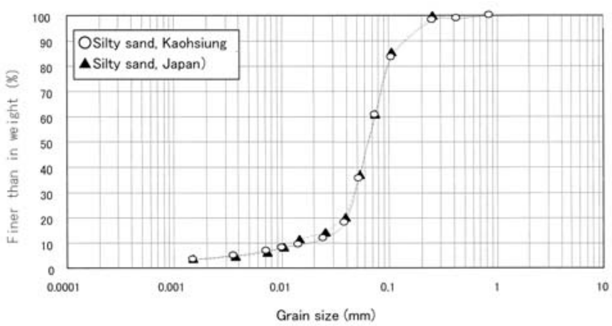


Fig. 9 Grain size distribution curves of silty sands used for the pinhole tests.

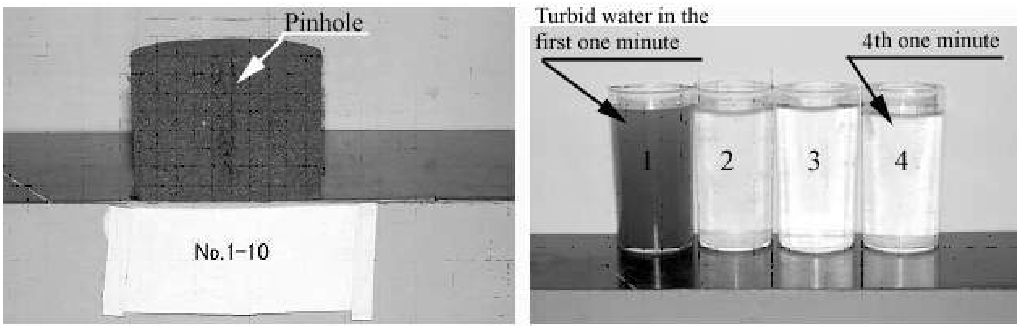
Table 1 Grading of two materials used for the pinhole tests.

Material	Kaohsiung sand	Japanese sand from Chiba
Dry density ρ_d (g/cm^3)	1.902	1.902
D_{60} (mm)	0.0651	0.0654
D_{50} (mm)	0.0746	0.0743
D_{10} (mm)	0.0168	0.0124
Uc	4.443	2.51
Specific gravity Gs	2.733	2.708

(1) Pinhole Tests

In order to examine the vulnerability of the silty sands at Kaohsiung to the internal erosion or piping, what might be called "Pinhole test" was carried out. The layout of the test system is displayed in Fig. 8. The sample 4cm thick and 5.17cm in diameter was sandwiched by highly pervious gravel layers at the top and bottom with filter meshes placed between the sample and gravel. A vertical hole 3mm in diameter was drilled as shown in Fig. 8. Water was then circulated through the sample. In this type of test, water is supposed to flow mainly through the pinhole. If the silty portion is erodible, the water coming out is expected to be muddy, but otherwise the water transparent.

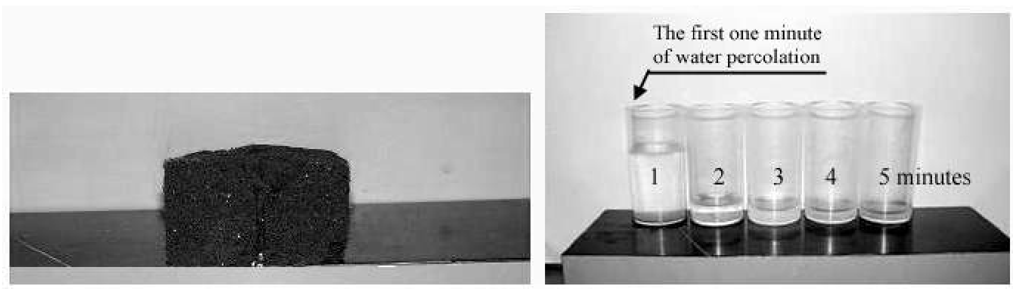
The silty sand from Kaohsiung tested had a grain size distribution as shown in Fig. 9. For comparison sake, another material from a site in Chiba, Japan, was secured and used for the same testing. The grading of this Japanese soil was almost the same as indicated in Fig. 9. It is to be noticed that both silty sands had an average grain size of about D50=0.075mm and fines content was about 50%. The physical characteristics of these two materials are shown in Table 1. The two samples were compacted so as to have the same wet density of 1.902 g/cm^3.



(a) Pinhole enlarged from 3mm to 5mm, visible erosion

(b) In the first one minute percolation, water was mud as seen in the left cup

Fig.10 Silt-contained sample from Kaohsiung.



(a) Diameter of the pinhole remained unchanged except local collapse at the top

(b) In the first one minute percolation, water was seen almost transparent as observed in the left cup

Fig.11 The results of the pinhole test on the Japanese silty sand.

1. Water was circulated first slowly with a low pressure through the sample to ensure saturation.

2. Water was then circulated under a pressure of 98kPa and colour of water coming out of the sample was observed. Pictures were taken every one-minute. Water percolation was continued for 5 minutes.

In the first series, the tests were conducted on disturbed samples, one from Kaohsiung and another from Japan. The result of the pinhole tests on a disturbed sample is presented in Fig. 10. For the disturbed silt-containing sand sample from Kaohsiung, the pinhole is seen enlarging to a diameter of 5mm from 3mm as displayed in Fig. 10(a). Correspondingly, the drained water from the bottom was muddy for the first one-minute period of water percolation as seen in the water colour in the left-side cup of Fig. 10(b). The result of the pinhole test on the Japanese silty sand is shown in Fig. 11. In contrast to the Kaohsiung soil, the circulation of water through the Japanese soil did not exhibit any appreciable change in colour in the first one minute of percolation as seen in Fig. 11(b).

There was no change in the pinhole diameter for the Japanese soil before and after water permeation except for a local collapse at the top. Thus, it may be conclusively mentioned that the silty sand from Kaohsiung is potentially susceptible to internal erosion as compared to the soil from Chiba, Japan, although they had almost the same grading.

(2) Specific surface test

To obtain another kind of index property for identifying the highly erodible nature of silty sand in Kaohsiung, what is called specific surface tests were conducted. In the Brunauer-Emmett-Teller (BET) method, the surface area is measured per unit weight of silt-size particle and expressed in terms of square meter divided by the weight in gram. If the specific surface is large, the particle is more of angular shape, and thus envisaged to become more difficult to move through the pores of the skeleton formed by coarser grains. In contrast, the particle of round shape with smaller value of the specific surface would be easier to move in the pores and therefore more erodible.

Two tests were performed for the same batch of silty sand from Kaohsiung having the grading shown in Fig. 9. For comparison sake, the tests were conducted also for the Chiba sand in Japan of which the grading is shown in Fig. 9. The results of the tests are shown in Table 2, where it may be seen that the specific surface area for Kaohsiung soil is about half of the value for Chiba soil from Japan. In unison with the results of the pinhole tests as mentioned above,

Table 2 Results of specific surface tests.

	(m^2/g) Sample 1	(m^2/g) Sample 2	(m^2/g) Average
Kaohsiung silty sand	3.2669	2.9540	3.1100
Silty sand from Chiba, Japan	6.2228	6.1469	6.1849

this observation of Kaohsiung soil shows that it is considered more susceptible to internal erosion due to seepage flow as compared to other soils.

6. CONCLUSIVE REMARKS

In the practice of subway construction in Kaohsiung, it has been known that the silty sand in that area is of peculiar nature being highly susceptible to erosion due to seepage. Although the silt portion is known to be non-plastic, there has been no way further on to scrutinize the nature of the silt. In an effort to grope for some gauge, what is called pinhole test and specific surface test were conducted for the Kaohsiung silt and also for silt from Japan. The results of these tests have shown that the silt from Kaohsiung is more erodible and has a smaller value of specific surface area than the silt in Japan.

This fact is indicative of the tendency of the Kaohsiung silt to be more liable to erosion as compared to other silts. The piping failure in the subway construction in Kaohsiung as descried above is considered as a consequence of such a peculiar nature of the local soil which had not explored until now. This incident is to be regarded as a typical example addressing an issue of new challenge in the area of geotechnical engineering.

ACKNOWLEDGMENT: In providing the draft of this paper, cooperation was obtained from many officers, engineers and researchers who have been earnestly involved in forensic investigations after the incident. The precise information regarding the features of the collapse in Kaohsiung was offered by the courtesy of the Kaohsiung Rapid Transit Construction (KRTC). The permission to include the results of the investigations was also given by KRTC. The authors wish to extend the most sincere thanks to the organizations and professionals as above for their overall cooperation and kind advice in preparing this paper.

REFERENCES

1) Chen, C.H. and Lee, W. : Forensic Investigation of a Disastrous Failure at the Arrival End of a Station of the Kaohsiung Mass Rapid Transit System, Proceeding of the International Conference on Forensic Engineering, Mumbai, India, 2007.
2) Hwang, A.B., Ishihara, K. and Lee, W. : Forensic studies for failure at an underground station, Proceedings of the Thirteenth Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Calcutta, India, 2007.
3) Ishihara, K. and Lee, W.F.: Forensic Diagnosis for Site-Specific Ground Conditions in Deep Excavations of Subway Constructions", Geotechnical and Geophysical Site Characterization, Proc. 3rd International Conference on Site Characterization, Taipei, pp. 31-59, 2008
4) Kenny, T. C. and Lau, D.: Internal Stability of Granular Filters, Canadian Geotechnical Journal, Vol. 22, No, 2, pp. 215-225, 1986.
5) Sherard, J. L., Dunningan, L. P., Decker, R. S. and Steele E.F.: Pinhole Test for Identifying Dispersive Soils," Journal of Geotechnical Engineering. GT1, ASCE, pp. 69-86, 1576.
6) Terzaghi, K. : Soil Mechanics; A New Chapter in Engineering Science, Journal of Institution of Civil Engineering, 12, pp. 106-141, 1939.