第17卷 第6期 岩石力学与工程学报 17(6):679～686
1998年12月 *Chinese Journal of Rock Mechanics and Engineering* Dec., 1998

FE Modelling of Seepage in Embankment Soils with Piping Zone

Yin Jianhua

(Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong)

Abstract A finite element model based on continuum mechanics is established to simulate the seepage flow in embankment soils with piping zone. The focus is placed on the piping zone length and permeability ratio k/k_0 and the influence on seepage flow. Main finite element results are presented and discussed. Measures for preventing piping failures are presented.

Key words piping, erosion, seepage, soil, embankment, finite element

分类号 TU974

1 INTRODUCTION

In China this year, unusual large flooding occurred in Yangtze River and other rivers in the northern region and the southern east regions of China. It was reported that piping caused a number of river embankment failures. The study on the piping mechanism and mitigation measures is therefore very important.

Failure by piping means that structures on foundation soils have failed by the apparently sudden formation of a pipe-shaped discharge channel or tunnel located in the soils or between the soils and the foundation. As the retained water rushes out of the dam or embankment, the width and depth of the water flow passage increases rapidly with time until equilibrium in water flow and stability of surrounding soil/structures are reached.

There are two different processes of piping failures. (1) Fine particles start to come out at springs near the downstream and proceed upstream along the base of the foundation or bedding plane or existing holes. Failure occurs as soon as a pipe-shaped channel (or eroded hole) is formed and a large amount of water comes out with very likely collapse of foundation soils and structures. This kind of failures is referred to as failures by sub-surface erosion[1]. (2) Due to increasing hydraulic gradient in the soil adjoining the downstream toe of the structure, the effective stress in the soil is reduced to zero and a large body of the soil suddenly rises up like " boiling ". The structure may lose resistance or support and then collapse. The second kind of failures is referred to as failures by heave.

The theory for calculation of the factor of safety against failures by heave is well established[1~2]. In this case, the factor of

---

1998年10月5日收到初稿，1998年10月26日收到修改稿。

safety F is defined as $F = W'/U$ where W' is the total downward effective weight (including surcharge if any) and U is the net upward pressure thrust. For uniform soils without surcharge, $F = i_c/i$ where i is the hydraulic gradient (usually in average), i_c is the critical hydraulic gradient and $i_c = \gamma'/\gamma_w = (G_s\text{-}1)/(1 + e)$ (γ' is the buoyant unit weight, γ_w is unit weight of water, G_s is specific weight of soil particles, and e is void ratio).

But, the theory for the failures by sub-surface erosion is not yet fully developed. It is found that even the hydraulic gradient i is smaller than i_c, piping in the sub-surface could occur. The failures by sub-surface erosion are the main area of this study. It is commonly understood that in the process of sub-surface erosion failure, fine particles come out through voids of coarse particles, gaps between soils and structures or the bedding planes. This movement of fine particles cannot be simulated by numerical models based on continuum mechanics. Discrete element methods may be utilized in this case. On the other hand, if we do not simulate the fine particle movement, rather than the seepage flow in the soils, the finite element method based on continuum mechanics is still valid. This is because that once the fine particles move out of the soil, the soil without fine particles remains and can be still considered as continuum. The soil without fine particles may have much higher permeability. This consideration justifies the use of a finite element method based on continuum mechanics for simulation of seepage flow in soils with piping channels.

Many factors may affect the formation of piping failures and the seepage flow in soils with piping channels, for example, soil profiles, dimensions, boundary conditions, soil permeability (linear or non-linear), degree of saturation, relationship of water content and pressure (or storativity), and stress-strain relationship of soils. The focus is placed on studying two factors: (1) the length of piping zone, (2) ratio of permeability of piping zone over the permeability of embankment soil. The influence of the two factors on seepage flow pattern, the maximum seepage velocity and total seepage rate (or flux) are examined. The results from this study may help us to have a better understanding on the seepage flow in soils with a piping zone and to prevent piping failures.

2 FE MODELLING

A finite element (FE) program named SEEP/W (1998) is used here to model seepage flow in soils with piping zone. Before discussing detailed FE modelling, two points of the FE modelling shall be mentioned:

(1) This FE model is not to simulate the piping process, rather than the seepage flow in soils when a piping zone has been formed and stabilised. Therefore the fine particle movement, permeability changes, void ratio changes and likely multi-phase flow in the piping zone are not considered in this FE model. A piping zone may develop in stages. This simplified FE model is considered to be a practical approximation to the real seepage flow situation.

(2) In real situation, the piping zone developed in the embankment soils may be an irregular three-dimensional (3-D) body and the seepage is 3-D in nature. However, 3-D finite element seepage modelling is very time-consuming, expensive, and difficult. The FE program SIGMA/W(1998) used in this study is a 2-D program for 2-D seepage analysis. This 2-D assumption may deviate from the real complicated 3-D situation. However, observations and conclusions from the 2-D FE modelling are believed to

be similar to those of 3-D seepage flow and are still of reference value. The above two points have also been used in references[1, 2] on the modelling and explanation of seepage flow in soils with a piping zone and piping process.

Fig. 1 is a typical river embankment (cross-section), FE mesh and boundary conditions. In Fig. 1, the water table in the river is at elevation + 29 m. The ground surface outside the river embankment is at + 10 m. The river bed is at elevation -10 mPD. The embankment slope inside and outside the river is all at 1.5 : 1 (Horizontal to Vertical). The embankment top elevation is + 26 m. In the middle and up-part of the embankment, a vertical wall (2 m wide and 13 m high) is installed. The top of the wall is at elevation + 32 m. The wall has 6 m above the top of the embankment and 7 m buried in the embankment.

Linear quadrilateral elements are used for most soils. Linear triangular elements are generally used in slopping area. Infinite elements are used at the right side of the domain, which is considered very long horizontally. The left vertical side of the domain is considered to be centre line of cross-section of the river. The right vertical side , left vertical side and the bottom side are considered impermeable. Inside the river, the boundary has a constant total head of + 29 m, the same as the water level. Outside the river, the water may flow out of the embankment and is assumed to flow on the slopping surface and/or the ground surface (probably in drainage channels or pipes in real situation). However, the exit point of the phreatic surface is not known exactly. In SEEP/W (1998), the boundary with possible exit point of the phreatic surface is considered to be a "review" boundary. The computer program can automatically search for the exit point and calculate the correct location of the phreatic surface. Thus, the boundary outside the river is considered to be a "review" boundary.

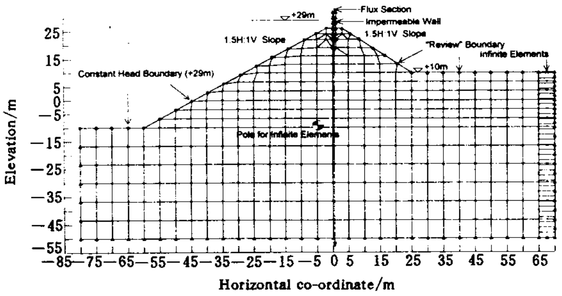
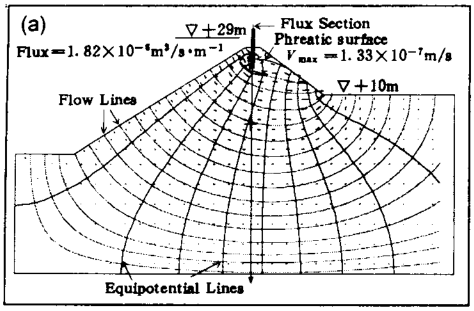


Fig. 1 Embankment profile, finite element mesh and boundary conditions

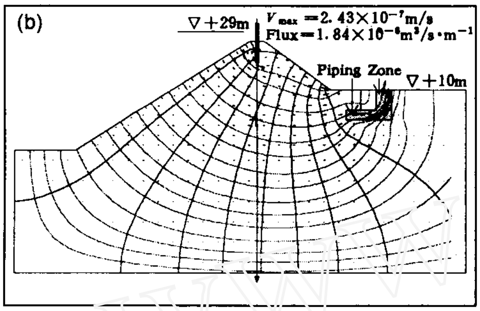
The first task of the FE modelling is to study the piping zone length and its influence on seepage flow. A pipe zone is assumed to develop gradually as shown in Fig. 2. There is no piping zone in Fig. 2(a). But the piping zone length increases gradually from 21 m in Fig. 2(b) to 92.5 m in Fig. 2 (g) (through the embankment foundation soil). The length of the piping zone is measured along the central line of the piping progressing direction. The length of the piping zone and the ratio of current piping length over the final piping length are listed in Table 1.

The wall is assumed to be impermeable. The main soil is considered to be a typical clayey silts with a permeability of $k_o = 10^{-7}$ m/s. The second task is to study the permeability of the soil in the piping zone and its influence on seepage flow. Since fine particles in the piping zone move out of the soil, the permeability of the soil without fine particles shall be higher than the surrounding soil. Thus permeability of the soil in the piping zone is assumed to vary from $k = 0.1$ m/s to $k = 2 \times 10^{-7}$m/s (see Table 2). The ratio of k/k_o

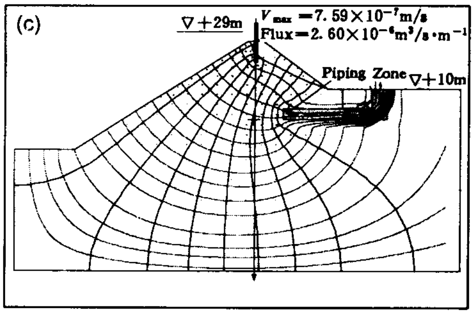
is also listed in Table 2.



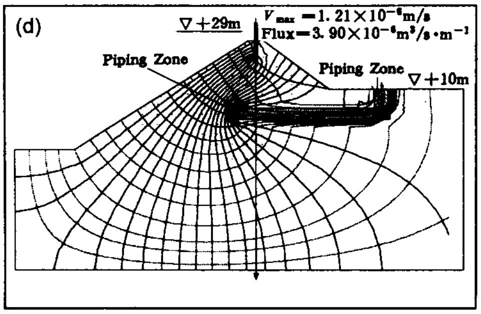
(a)



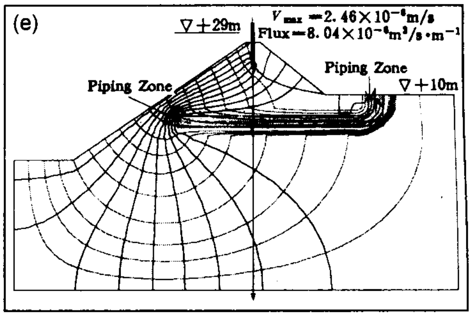
(b)



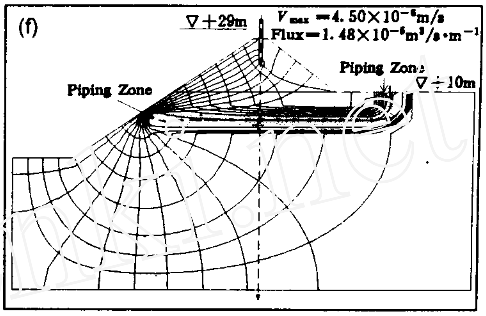
(c)



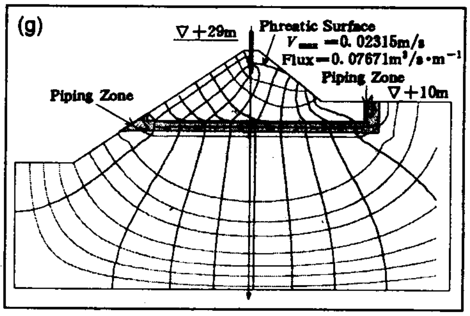
(d)



(e)



(f)



(g)

Fig. 2 Progressing of piping zone and increase in maximum velocity and total flux-cases in (a), (b), (c), (d), (e), (f) and (g)

Table 1 Length of piping zone and main FE results

Piping Zone Length/m	Length Ratio	$V_{\max}$ /m · s^{-1}	Flux /m^3 · s^{-1} · m^{-1}
0	0	1.33×10^{-7}	1.82×10^{-6}
21	0.227	2.43×10^{-7}	1.84×10^{-6}
41	0.443	7.59×10^{-7}	2.60×10^{-6}
56	0.605	1.21×10^{-6}	3.90×10^{-6}
76	0.822	2.46×10^{-6}	8.04×10^{-6}
86	0.930	4.50×10^{-6}	1.48×10^{-5}
92.5	1	0.023 15	0.076 71

Table 2 Permeability of soil in piping zone and main FE results

k /m • s^{-1}	k/k_0	V_{max} /m • s^{-1}	Flux /m^3 • s^{-1} • m^{-1}
1×10^{-7}	1	1.33×10^{-7}	1.82×10^{-6}
2×10^{-7}	2	1.34×10^{-7}	1.88×10^{-6}
1×10^{-6}	10	2.49×10^{-7}	2.24×10^{-6}
1×10^{-5}	100	7.71×10^{-7}	3.33×10^{-6}
1×10^{-3}	1×10^{4}	1.10×10^{-6}	3.89×10^{-6}
1×10^{-1}	1×10^{6}	1.21×10^{-6}	3.90×10^{-6}

The FE results and discussion are presented in the following section.

3 FE RESULTS AND DISCUSSION

3.1 Influence of Piping Zone Length on Seepage Flow

In this study, the permeability of the soil in the piping zone is assumed to be k = 0.1 m/s. The piping zone length is listed in Table 1. The main FE results are shown in Fig. 2. The maximum velocity value and the total flux (seepage rate) are presented in Table 1. Fig. 2(a) shows the equipotential lines, flow lines, seepage velocity vector, and phreatic surface in the case of no piping. It is noted that the equipotential lines and flow lines are computed by SEEP/W and they are not the flow net. In Fig. 2(b), a piping zone is assumed (L = 21 m). It is observed by comparing Fig. 2(b) to Fig. 2(a) that the flow pattern is changed slightly, the maximum velocity magnitude is increased from 1.33×10^{-7}m/s to 2.43×10^{-7}m/s. The total flux is changed little.

As the piping zone develops as shown in Fig. 2(c), (d), (e) and (f), notable changes are: (1) the more water moves into the piping channel with more and more flow lines going through and near by the piping channel, (2) the phreatic surface is lowering down gradually, and (3) both maximum velocity and flux increase gradually.

When the piping zone is through, it is noted as shown in Fig. 2(g) that the phreatic surface returns to a higher level closer to the position in Fig. 2(a). Nearly all water flows in the piping channel with relatively very large velocity vectors in the piping channel and nearly invisible vectors in other regions as shown in Fig. 2(g).

The relationships of the maximum velocity and the total flux versus the piping length ratio are shown in Fig. 3. The ratio 1 means the case in Fig. 2(g). It is seen that when the piping zone goes through the embankment soil, both the maximum velocity and the total flux are increased dramatically.

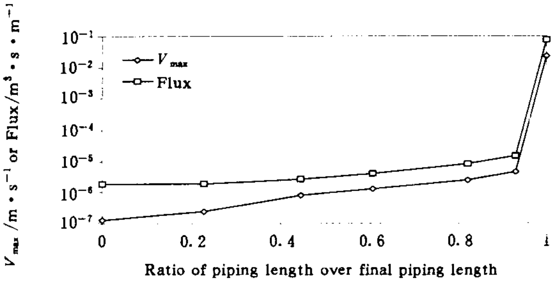


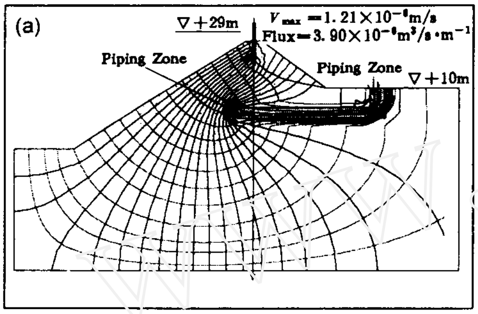
Fig. 3 Relationship of V_{max} and total flux in logarithmic scale vs ratio of piping length over final piping length

3.2 Influence of Piping Zone Soil Permeability on Seepage Flow

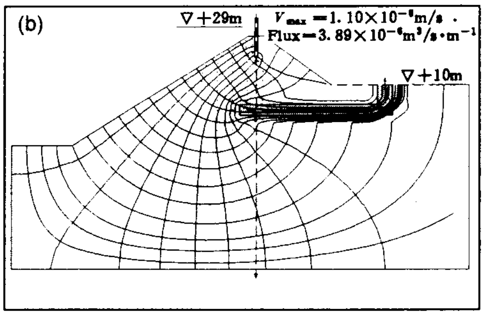
The piping zone length in Fig. 2(d) is fixed in this study. The permeability of the soil in the piping zone is reduced gradually from k = 0.1 m/s in Fig. 4(a) (or Fig. 2(d)) to k = 2×10^{-7}m/s in Fig. 4(e). The values of permeability k and ratio k/k_0 are listed in Table 2. Fig. 4 shows the main FE results. The maximum velocity value and the total flux value are listed in Table 2. It is seen in Fig. 2 that more and more water flows into the piping channel as the ratio

k/k_0 increases, see Fig. 4(e), (d), (c), (b) to (a). The phreatic surface is lowering down gradually as the ratio k/k_0 increases.

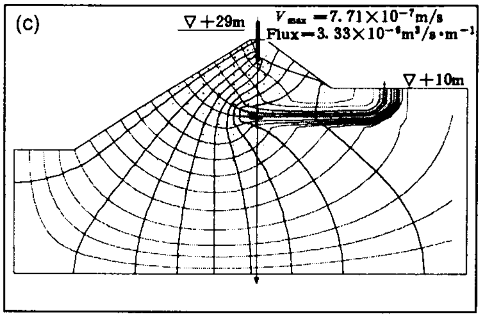
Fig. 5 shows the relationships of the maximum velocity and the total flux versus ratio k/k_0. It is seen that when k/k_0 is 2, both V_{max} and flux increase little. But when k/k_0 is 10, both V_{max} and flux increase dramatically. But when k/k_0 is larger than 1 000, both V_{max} and flux increase less and less. The dramatic increase in both velocity and flux is an indication of high potential for further piping zone enlarging.



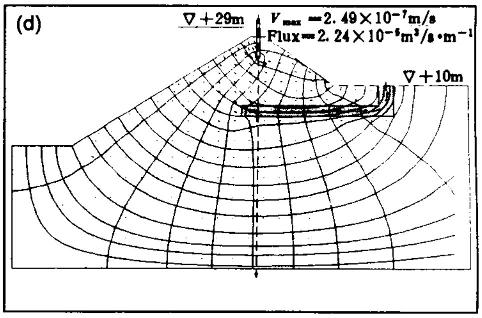
(a) $k/k_o = 10^6$



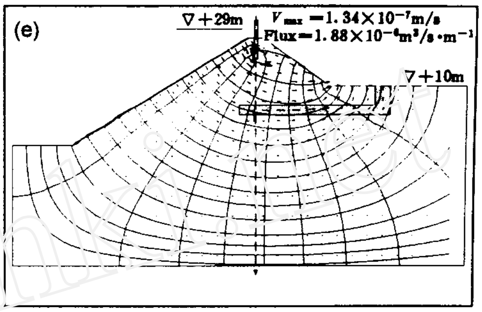
(b) $k/k_o = 10^4$



(c) $k/k_o = 100$

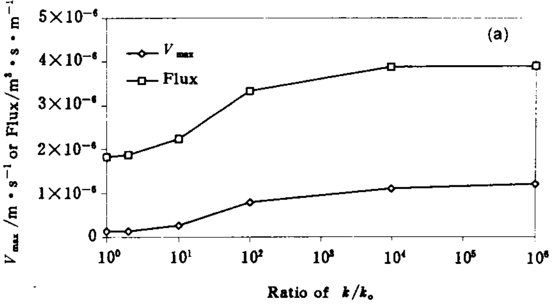


(d) $k/k_o = 10$

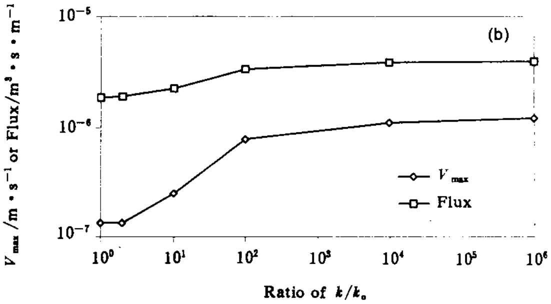


(e) $k/k_o = 2$

Fig. 4 Piping for of different permeability ratio (k/k_o)



(a) arithmetical scale



(b) logarithmic scale

Fig. 5 Relationships of V_{max} and total flux vs permeability ratio k/k_o in logarithmic- V_{max} and total flux in (a) and (b)

There is one in common in Fig. 3 and Fig. 4, that is, more and more water flows into the piping channel as both the piping length and the ratio k/k_0 increase. This phenomenon is called flow concentration. This means that once a piping zone is formed, this zone may become bigger and bigger. This implies that the larger the permeability ratio k/k_0, the higher the piping danger. Once a small piping zone occurs, remedial measures must be taken to prevent the piping zone from increasing.

4 PREVENT FOUNDATION SOIL FROM PIPING FAILURES

4.1 New Geotechnical Structures

For new geotechnical structures, careful considerations in design and construction can prevent soils from piping failures. Drainage filters shall be well designed and constructed. In Hong Kong, it is recommended that granular filters satisfy at least[4]: (1) D_{15} (of filter soil) $< 5 \times D_{85}$ (of fine soil to be retained)-retention criterion; (2) D_{15} (of filter soil) $> 5 \times D_{15}$ (of fine soil to be retained)-permeability criterion; where D_{15} (or D_{85}) is the particle size at which 15% (or 85%) of the soil (filter soil or retained soils) is smaller. The retention criterion means that the pores in the filter must be small enough to prevent infiltration (or moving out) of the fine soils being drained (of retained). The permeability criterion means that the filter must be much more permeable than the material being drained (or retained).

For geotextile filter, the criteria are[4]:

(1) O_{15} (of geotextile filter) $\leqslant D_{85}$ (of fine soil to be retained)-retention criterion; (2) O_{90} (of geotextile filter) $\geqslant D_{15}$ (of fine soil to be retained)-permeability criterion; where O_{15} (or O_{90}) is the particle size at which 15% (or 90%) by weight of particles are retained on the geotextile upon dry sieving using ballotini (glass beads).

Except for the filters, the segregation of fine particles from coarse particles shall be prevented so that the permeability ratio of the adjacent soils is less than 2. The hydraulic gradient shall be smaller than the critical hydraulic gradient with a safety factor of 1.5～2.

4.2 Existing Geotechnical Structures

If a geotechnical structure (deep excavation or river embankment) has been built and initial piping is observed, the following measures may be taken to prevent piping from further development:

(1) To reduce the hydraulic gradient and seepage quantity in the foundation soils. For example, in the case of deep excavation, sheet-piles (diaphragm wall or other similar structures) shall be installed deeper to reduce hydraulic gradient and seepage quantity. For river embankment, impermeable (or less permeable) structures may be driven in the embankment to reduce seepage flow. Geo-membrane may be laid on the embankment slope facing the river to reduce seepage quantity.

(2) To increase the resistance or strength against piping failure and overall stability of the structures. For example, in the case of deep excavation, counter-weight (normally granular soils and concrete) with filters may be constructed step by step at the bottom of the excavation to increase resistance to failure of piping heave. In other cases, quick chemical grounting and installation of structures (or piles) may be used.

The above measures are not exclusive. Development of new materials and new methods for preventing piping is an interesting area of research.

5 SUMMARY

In this paper, a FE model based on continuum mechanics is established to simulate the seepage flow in the embankment soils with piping zone. The focus is placed on the piping zone length and permeability ratio k/k_0 and the influence on seepage flow. Main FE results are presented and discussed. Based on the results, it is found that the larger the piping length and/or the k/k_0 ratio, the more water flows toward or into the piping zone (or channel), in other words, the more water flow concentration near the piping zone. It is also found that both the maximum velocity and total flux increase as the piping zone length and/or the k/k_0 ratio increase. When k/k_0 ratio is 2 ~ 100, a dramatic increase in both the maximum velocity and total flux is observed. But when k/k_0 ratio is larger than 100, the increase is getting less and less.

Measures for preventing soils from piping failures are presented. These measures may be adopted depending on specific situations.

REFERENCES

1 Terzaghi K, Peck R B, Mesri G. Soil Mechanics in Engineering Practice (3rd Edition). New York: John Wiley & Sons, Inc., 1996

2 Cedergren H R. Seepage, Drainage, and Flow Nets (3rd Edition). New York: John Wiley & Sons, Inc., 1989

3 SEEPW. SEEP/W program and manual (Version 4.2). Calgary, Canada: Geo-Slope International Ltd., 1998

4 Geotechnical Engineering Office. Geoguide 1: Guide to Retaining Wall Design (Second Edition). Hong Kong: 1993

中国土木工程学会隧道及地下工程分会第十届年会在西安召开

由中国土木工程学会隧道及地下工程分会主办、中国铁路工程公司和中国铁路建筑总公司承办的第十届年会暨以“走向二十一世纪的隧道及地下工程”为主题的学术讨论会于1998年10月17～20日在古都西安铁道部第一勘测设计院西安分院召开。这是继1996年10月在北京市召开的第九届年会之后，又一次由分会主办的全国性隧道及地下工程的大型学术会议。

来自全国各地近百个部门、单位和厂商的大约400名理事、论文作者和代表参加了会议，是千年更替、世纪之交的一次难得的盛会。

钱七虎、王梦恕院士以及郑颖人、杨林德教授等分别在学术会议上作了专题报告，并分成了隧道施工、地下铁道、地下空间、通风与防排水及隧道力学等5个分会场进行了学术交流与讨论。

这次会议还结合目前正在用掘进机(TBM)施工的我国最长的铁路隧道——秦岭隧道的设计和施工技术进行了学习和交流。这座隧道全长18.456 km，也是亚洲最长的铁路单线隧道，建成后在长度上将有20项指标突破亚洲纪录。

会议期间还召开了学会第四届常务理事会，确定了新一届理事人选。轩辕啸雯同志连任第五届理事长，同时对第十一届年会的时间和地点进行了初步协商。

（范文田供稿）