Numerical Analysis for Crack and Opening of Keystone Block Wall

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요 지

Geogrid를 보강재로 사용하는 Keystone block 보강토 옹벽의 설계와 시공에 있어서 기존의 연구와 설계기준들은 전부 직선 구간에 관한 것들로서 곡선구간의 설계 및 시공에 관한 연구는 부족한 실정에 있다. 따라서, 본 연구에서는 돌출형 곡선 부분의 시공성 및 구조적인 안정성을 검토하기 위하여 직선구간의 NCMA 해석법과 이를 이용한 곡선구간의 해석 및 시공상의 문제점 및 그 원인을 분석하여, 이에 따른 설계 및 시공시의 문제점과 대책을 강구하는데 그 목적이 있다. 곡선구간을 Shell 해석에 의해 직선구간과의 변위 및 응력들의 차이점을 규명하고 이를 이용하여 돌출형 곡선구간의 Keystone block wall의 문제점 분석 및 대책강구를 위한 기초자료 연구에 목적을 두고 있다.

ABSTRACT

In the design and construction of Keystone block reinforced wall with geogrid, previous studies and current design codes have been focused on straight area of wall. However, research on the behaviour of wall in curved area is required.

This study is to investigate the structural stability of wall and problems during construction in curved area. Previous analyzing methods, usually used for straight area of wall, have been reviewed to find any problems in applying to stability analysis of curved area.

Thus, the purpose of this study is to show how to analyze the straight area of Keystone block wall first, and then turn this to use for analyzing various significance, concerning the design or construction of curved high keystone block wall.

From this investigation and study, the aim is to find out the differences of the displacement and the stress behavior on retaining wall between straight and curved conditions by F.E.M, using the shell analysis theory.

Keywords : Reinforced Walls, Geogrid, Keystone Block Walls, NCMA Method, Buckling, Coherent Gravity Structure Theory, Tie Back Structure Theory

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1. Introduction

Recently, Keystone block wall is world-widely used with geogrid as a reinforcing member. So far, all previous studies are related with straight area design and construction, provided that analysis can be more precise, relatively. However, for curved area, studies have rarely made where retaining wall should meet rounding angle. This study is mainly concerned about construction possibility with structural stability at curved area. Furthermore, it is to establish the solution and to investigate the various significances against expected problems which are associated with practical construction and design(Bathurst, 1994; Colin J.F.P., 1996; Tatsuoka Fumio, 1994).

2. The Mechanism of Keystone Block Wall

Keystone block wall is made up of reinforcing members, connection pin and back fill soil materials. Resistance force against lateral earth pressure is controlled by the interconnection of those components. Thus, if any member defects, insufficient interconnection or ill condition of geogrid installation and compaction are provided, buckling and crack phenomenon are to be developed. A big difference between reinforced retaining wall and conventional rigid retaining wall is how to consider failure surface and coefficient of lateral earth pressure. Two different design methods have been used; tie-back anchorage system using conventional retaining wall design method, and coherent gravity structure method (composite gravity retaining wall) established from the in-situ testing and experimental data(Das B.M.,1993; Berg R.R.,1993; Ingold T.S.,1995).

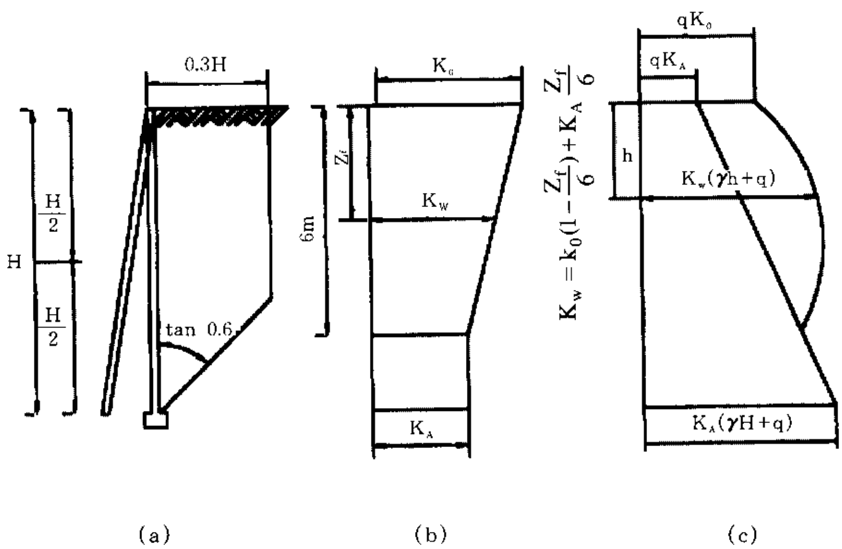


Fig.1 Theory and failure diagram of coherent gravity structure

Judging from many in-situ test results, coherent gravity structure design method shows that lateral earth pressure at the upper part of retaining wall is in the stress state at rest and the bottom part is approaching to the active stress state. The displacement of facing panel and distribution of lateral earth pressure are shown in Fig. 1(a), 1(c), respectively(Mitchell J.K.,1985; Koerner R.M.,1986).

Reinforced retaining wall has been designed in terms of internal and external stability, and usual stability analysis takes NCMA(National Cement Masonry Association) method.(Simic, M.R., Batherhurst, R.A., and Berg, R.R.,1993)

2.1 External stability

External stability analysis, as we know, includes sliding failure along wall base, overturning about wall toe, bearing capacity failure of the base. Furthermore, overall slope stability check and structure destruction by settlement should be considered. But the acceptable safety factors are different from the ordinary retaining walls.(Lovell C. W., 1994)

2.2 Internal stability

Internal stability is to check reinforcing member failure against tensile force and pull out force. Based on the length of reinforcement which is obtained by external stability, vertical spacing (S_v) is determined as shown in the following formula.(Koerner R.M.,1986; Colin J.F.P.,199; Palossy L., et al, 1995; Lamb P.C.,1990; Berg R.R.,1993)

$$S_v = \frac{\sigma_G}{\sigma_h \times F_s} = \frac{\sigma_G}{\gamma z K_w F_s}$$

where, σ_G : allowable tensile strength of reinforcement,

σ_h : horizontal stress,

F_s : factor of safety

γ : unit weight of backfill soil,

z : depth,

K_w : coefficient of active earth pressure of backfill soil.

$$K_w = k_0(1-\frac{h_i}{h_0}) + k_A \frac{h_i}{h_0} \qquad \cdots h_i \le h_0 = 6\text{m}$$

$$K_w - k_A \qquad \cdots h_i \rangle h_0 = 6\text{m}$$

(1) The maximum vertical installation space

The maximum tensile force (T_i) mobilized in i th reinforcement per unit width due to soil's self weight of backfill and surcharge is as follow;

$$T_i = K_w(\gamma h_i + q)S_{vi}$$

where, q : surcharge,

S_{vi} : vertical space of reinforcing members.

Therefore, if total tensile force(T_i) does not exceed the allowable tensile strength of reinforce member, the maximum vertical installation spacing will be

$$S_{v(max)} = \frac{\text{allowable tensile strength}}{T_i}$$

(2) Estimating width (b) and cross section area (A_{st}) of reinforcing member For the tensile force of reinforcing member, determined as shown in the above, we can calculate required cross section area and width of reinforcing member. The cross section area and the width of each member can be estimated by the tensile capacity and pull out failure strength with the following formula.

$$A_{st} = \frac{T_i}{\sigma_G}, \qquad b = \frac{F_s \times T_i}{2f^* L(\gamma_i h_i + q)}$$

where, σ_G : allowable tensile strength of reinforcement,

L : length of reinforced members,

f^* : interaction coefficient of reinforcing members with backfill soils,

F_s : safety factor.

(3) Pull-out failure of reinforcing members

In the depth (h_i), effective adherence length of the reinforcing members (L_{ip}) and total anchorage force (T_{ai}) of the n th layers can be estimated with the following formula.

$$T_{ai} = \frac{L_{ip} \times 2f^* \tan(\gamma h_i + q)}{F_s}$$

The two sides of reinforcing member should be considered, whether surcharge exists or not, in reviewing pull-out capacity. If tensile force exceeds the allowable tensile strength of reinforcing member, the value of pull-out capacity should be restricted within allowable tensile strength of reinforcing members. Therefore, we must design that total tensile force(T_i)should not exceed the allowable tensile strength and total anchorage force (T_{ai}) of reinforcing members.

3. In-situ Test

The model used for the in-situ test and analysis is considered as structural binding with fiber glass pin as shown in Fig. 2.

The followings are In-situ analysis conditions: height of wall is 14.7 m, compression strength of Keystone block is over 240 kg/㎠, friction angle of reinforced backfill soils, retained backfill soils and foundation soils are all identical to the value of 32(degree), unit weight of backfill soils is 1.9 t/㎥, surcharge is 0 t/㎥, SR110 geogrid (Netlon's product)was used, whose allowable tensile strength is 4.05 t/m^2.

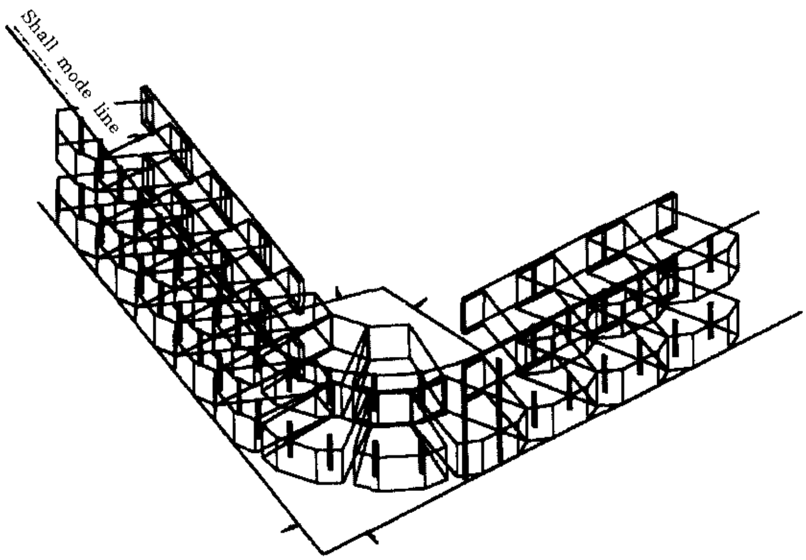


Fig.2 Solid body of keystone block retaining wall

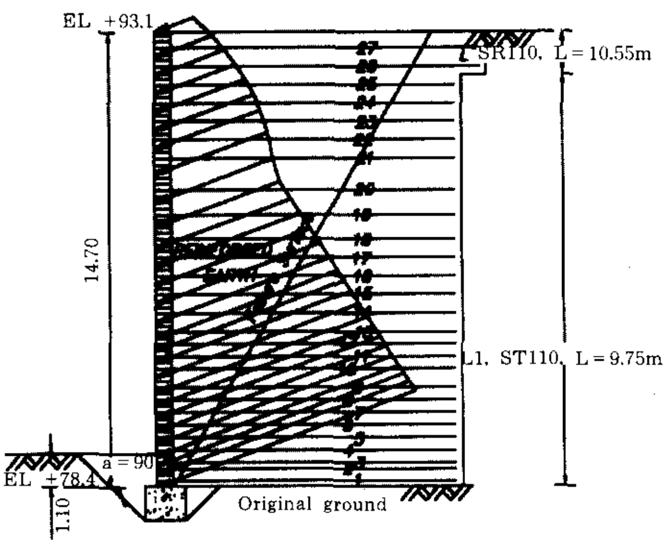


Fig.3 Diagram of lateral earth pressure of each position on analysis section

4. Analysis of Case Histories of Keystone Block Wall

4.1 Stability of Straight Area

After reviewing the section of straight area, as shown in Fig. 3, according to NCMA method , stability analysis of curved area is executed as shown in Fig. 2.

Internal stability results of the straight area are shown in Table 1 and distribution of lateral earth pressure is also shown in Fig. 3. External stability is stable, because safety factors of sliding, overturning and bearing capacity are 1.92, 3.05 and 4.21 respectively, which are greater than their allowable safety factor. Average safety factors of internal stability displays $F_s = 1.97$. But actually, stability of 19th and 27th reinforcing members is a little bit below the allowable safety factor, but doesn't affect overall stability.(Simic M.R.,1990; Simic, M.R., Batherhurst, R.A., and Berg, R.R.,1993)

Table 1. Results of analyzing internal stability

Geogrid No.	Geogrid Location	Total Length	Effective Length	Ki	Pullout Capacity	Tensile Force	Fs, for Pullout	Remarks
1	0.5	10.55	1.80	0.46	4.05	0.25	5.63	
2	1.1	10.55	2.15	0.43	4.05	0.50	7.29	
3	1.7	9.75	1.69	0.41	4.05	0.74	5.44	
4	2.3	9.75	2.04	0.39	4.05	0.96	4.22	
5	2.9	9.75	2.39	0.37	4.05	1.15	3.52	
6	3.5	9.75	2.73	0.35	4.05	1.31	3.08	
7	4.1	9.75	3.08	0.33	4.05	1.96	2.06	
8	5.1	9.75	3.66	0.30	4.05	2.43	1.67	
9	5.9	9.75	4.12	0.28	4.05	2.33	1.73	
10	6.7	9.75	4.58	0.27	4.05	2.24	1.81	
11	7.3	9.75	4.93	0.27	4.05	2.11	1.92	
12	7.9	9.75	5.27	0.27	4.05	2.28	1.78	
13	8.5	9.75	5.62	0.27	4.05	2.45	1.65	
14	9.1	9.75	5.97	0.27	4.05	2.63	1.54	
15	9.7	9.75	6.31	0.27	4.05	2.32	1.75	
16	10.1	9.75	6.54	0.27	4.05	1.94	2.08	
17	10.5	9.75	6.78	0.27	4.05	2.02	2.00	
18	10.9	9.75	7.01	0.27	4.05	2.63	1.54	
19	11.5	9.75	7.35	0.27	4.05	2.75	1.47	
20	11.9	9.75	7.58	0.27	4.05	2.29	1.77	
21	12.3	9.75	7.81	0.27	4.05	2.37	1.71	
22	12.7	9.75	8.05	0.27	4.05	2.44	1.66	
23	13.1	9.75	8.28	0.27	4.05	2.52	1.61	
24	13.5	9.75	8.51	0.27	4.05	2.60	1.56	
25	13.9	9.75	8.74	0.27	4.05	2.00	2.03	
26	14.1	9.75	8.85	0.27	4.05	2.04	1.98	
27	14.5	9.75	9.08	0.27	4.05	2.79	1.45	
sum					106.34	54.07	1.967	

4.2 Cracks and Buckling at the Angled Portion

Test results of retaining wall designed by using the NCMA method showed that cracks in perpendicular direction were well developed as much as 50~60 mm and the gab spacing between block to block(opening) is in the range of 50~60 mm. Buckling also took place.

Perpendicular cracks connected together on the wall indicate that there was significant facing displacement. Buckling is considered to be caused by strength defects of Keystone block itself, misplacement of backfill, defect on inter-connection of geogrid to pins, shortage of geogrid number, etc.

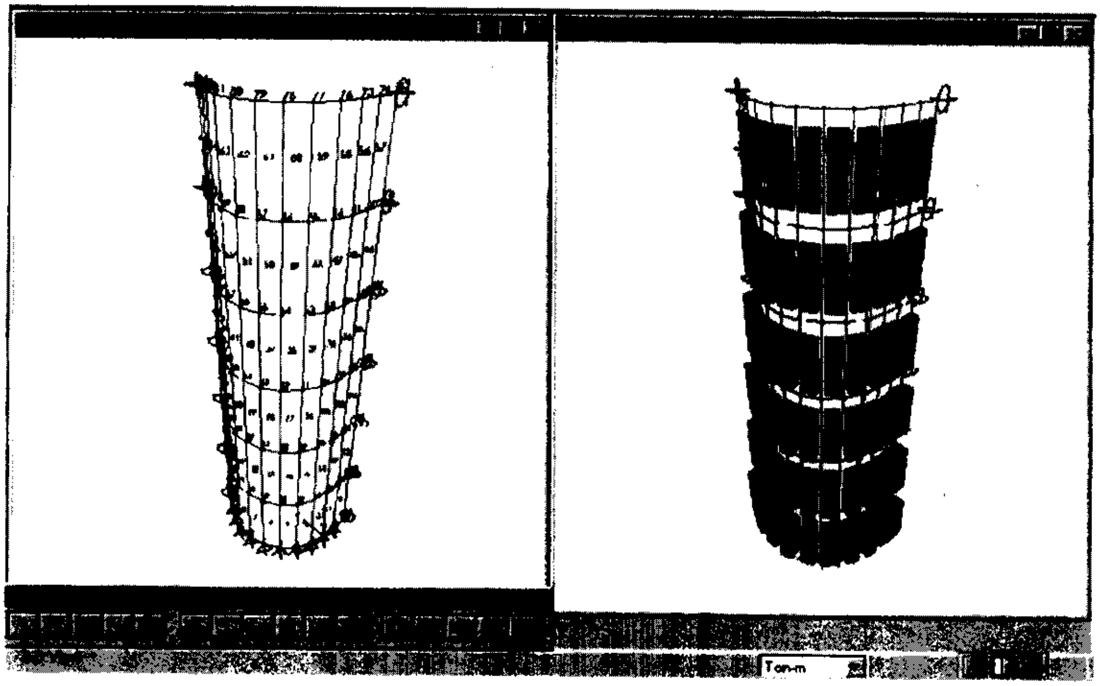
Photo 1. Cracks and opening at peak point of angled portion

Curved area, projected angle portion, has different construction conditions such as surcharge and earth pressure compared with straight area for which the theoretical mechanism has been used. Therefore, a different analysis method from NCMA method should be used. In this study 『SAP 2000』is used for the Keystone block wall analysis of cracks and buckling on the block wall as a shell plate by Finite Element Analysis Method.(CSI, 1997)

It is assumed that each Keystone block is one of the shell element. And the straight line area of angled portion side is limited by 1.0m, because of the amount of calculation problem, instead of setting the range to the section affected by changing Keystone block's tensile stress.

Therefore, if the full nodes in order to corresponding to the behavior of real structure should be used over 1178 nodes, the cluster of 5 blocks is considered as a shell element. In this analysis, 84 joints and 66 shell elements are used for the modeling, the thickness of Membrane Element and Plate Bending Element are treated as effective section area of

Keystone block. Block is also connected to block by glass fiber pin(diameter 12.7mm) so that it is assumed that thickness of Membrane Element and Plate Bending Element is less than 10mm. For boundary conditions, assuming that lower level of wall is fixed to both side of local coordinate x, y, and left and right end part of wall is hinge, x is fixed. Coulomb's earth pressure is applied against shell element as shown in Fig. 4(b).



(a) Shell model (b) Earth pressure applied shell element

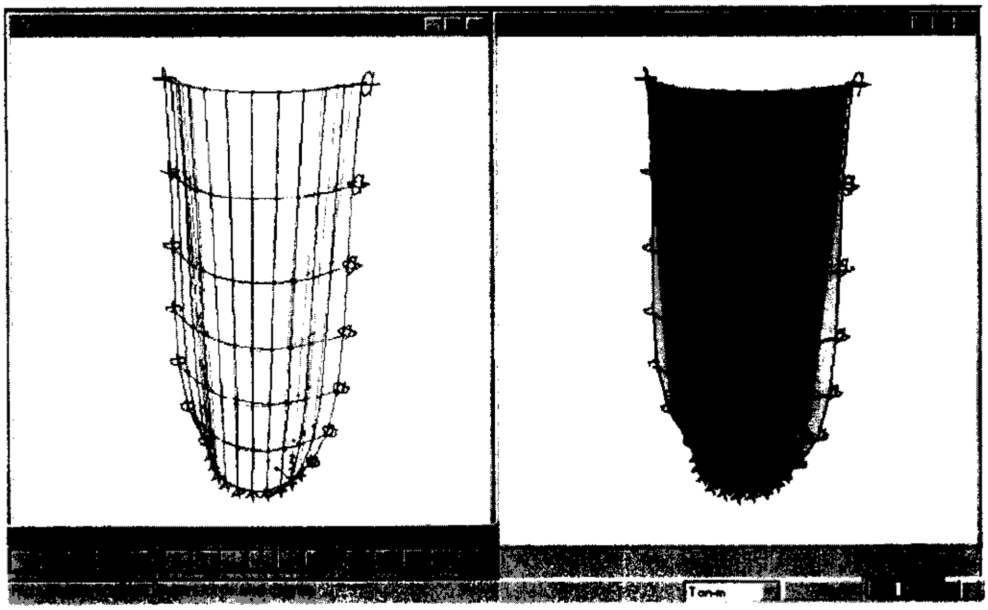
Fig.4 Analytical modeling of shell and earth pressure distribution

Fig. 5 shows a diagram of Keystone block wall deflection after construction by wall height of 6.0m at once. Wall displacement is insignificant but end part of wall section moves to forward, the peak point of angled portion moves to backfill soils. Tensile stress on shell element is developed to the direction of wall height at the peak point of angled portion. That corresponds to actual behavior in-situ, as shown in photo 1, where cracks develop vertically, and as shown in photo 2, displacement at the peak point of angled portion of wall is developed to the direction of backfill.

4.3 Opening & Cracks to Keystone Block Wall

As a reinforced member, Geogrid plays the role of joining the block, interconnected by pins, to the backfill soil material together, and it leads to the increase of overall shear strength of reinforced backfill materials by means of compaction after backfill soils placement.

In curved area, unlike straight area of wall, geogrid cannot be tightened perfectly to the block



(a) (b)

Fig.5 Deflection diagram at angled portion of wall and distribution of stress in shell straight element

Photo 2. Displacement at the peak point on angled portion in curved zone(GL. 0m)

because of gap between geogrid rib and connection pin. Furthermore, geogrids will be overlapped each other, so in order to obtain complete interconnection effects and to prevent them from sliding along with their surface, more vertical spacing than 7.5 cm should be taken into account at least(NCMA). Practically, there is a difficulty in installing geogrid by more than 7.5 cm of vertical spacing, layer by layer, at the projected zone.(Simic. M.R., Batherhurst, R.A., and Berg, R.R., 1993)

It will be also noted that Keystone block thickness is considered 20 cm in the process of section analysis. For technical design, it is true that block strength itself, shear strength of pin, interconnection joint-force of pin and block, and so on, are neglected for internal stability check at linear zone(straight zone) expected. Also the minimum force of frictional resistance or pull-out strength between backfill soils and reinforced member is used for technical design to check internal stability. Even though those items are neglected for stability in straight zone, they cannot be negligible for curved zone stability, because many unexpected problems are to be there. Usually these problems would be so complex that a certain thing cannot be pointed out as a main reason. Nevertheless, in projected zone, it is believed that tensile force between pins brings about many problems, mainly, as lateral earth pressure acts on the wall. We can think of a chain-belt that is linked by pins to the blocks, and leads to this tensile force in time. Once tensile force is applied to the blocks then it evokes cracks at the joint of pin, and it takes place an opening gap between blocks. It should be also noted that the maximum bending tensile stress of Keystone block is 65.0(t/m2). From analyzed results, it shows that the maximum tensile stress increases up to 270.0(t/m2) at the angled portion of wall in curved area zone(Standard Specifications of Concrete, 1996). So there is a possibility of cracks being occurred on the block, considering allowable bending stress with expected possible stress.

As a results of in-situ test, cracks and openings of the wall in curved area are developed vertically continuous along with wall surface, so these phenomena are delivered from external instability of wall rather than lacking of shear strength of block material.

Controversially, if there is cracks locally somewhere on the blocks, wall member strength itself may be insufficient. Discontinuous cracks, however, do not have an effect on overall structural stability of reinforced retaining walls.

5. Conclusions and Recommendations

In the process of design and construction of reinforced retaining wall with geogrid, having a projected geometry, it is required to change the method of design and construction because of its flexibility unlike the conventional design codes used for straight area of wall. From results of in-situ test and analysis, followings can be summarized.

1. In designing and constructing the block-type reinforced retaining wall, high backfill wall is more advantageous theoretically due to increasing pull-out resistant capacity, but the higher the wall is, step-by-step construction method is the better because is eliminates various problems during construction.
2. Judging from this study of reinforced retaining wall with geogrids, unlike the rigid reinforcing members, its behaviour is mainly governed by pull-out resistant capacity related to interaction between soil and geogrid, rather than tensile strength of geogrids.
3. According to NCMA criteria, spacing between geogrids to install is required to keep up 7.5 cm at least, but this is not suitable for curved area because of difficulty of its installation.

Thus such a specification is used for the practical purposes. As a results of analysis, the wall in curved area behaviors just like chain belt system, and significant displacement of projected-type wall may occur to the direction of backfill soils at peak point of angled portion in curved zone.

4. From in-situ test results with the wall being 14 m high and having 74° curved zone, it was found that "cracks" and "opening" occurred during construction at the stage of low fill placement. And the peak point of angled portion, curved zone, is to be undergone tensile stress, so there will be tension cracks. From this viewpoint, it is needed to avoid construction in curved zone because of angled portion. Otherwise, strict quality management should be required during the whole construction period.

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(received on May, 13, 1998)