Forensic analysis of failure of retaining wall

G L Sivakumar Babu ^{i), ii)}, P Raja and P Raghuveer Rao ⁱⁱⁱ⁾

i) Professor, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

ii) Former Project Associate, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

iii) Senior Scientific Officer, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

ABSTRACT

In this paper, results of forensic analysis of a cantilever retaining wall for road approach embankments which showed distress in the form of translation, vertical settlements and rotation is presented. Extensive geotechnical soil investigation and field measurements of distress are collected. The paper presents prominent causes of failure of cantilever retaining wall using forensic geotechnical investigation. Back analysis of the cantilever retaining wall is performed using classical conventional methods and finite elements analysis. From the results of the conventional analysis and finite element methods, it is observed the retaining wall designs based on prescriptive guidelines may not lead to satisfactory designs and considerations of deformations is important. Back analysis of failure showed that the mechanism of failure is a combination of sliding and overturning and the deformations are in conformity with the predictions obtained from the numerical analysis.

Keywords: forensic analysis, retaining wall, distress patterns

1 INTRODUCTION

Forensic geotechnical engineering is the investigation of the possible causes and processes of distress in a structure that is not able to perform the intended use. Such a critical analysis provides answers to understand the causes of failure. It also gives strong inputs to rehabilitation of structure. The normally adopted standard procedures of testing, design and construction are not adequate for the forensic analysis in majority of cases. The forensic geotechnical engineering differs in many ways from design geotechnical engineering. Generally, design geotechnical engineering involves preliminary investigation, standard field and laboratory investigation, design, construction and evaluation of performance. The forensic investigations involve fresh field and laboratory tests apart from collection of all available data as well as distress measurements. The test parameters and design assumptions in the forensic analysis will have to be representative of the actual conditions encountered at site. The design procedures are mostly stress based, based on limit equilibrium of failure modes such as shear failure, sliding overturning etc. On the other hand, the forensic analysis has to be deformation based to understand the distress pattern. It often needs to include: collection of data, characterization of distress, development of failure hypothesis, diagnostic tests and back analysis. In the present case forensic analysis of cantilever retaining

wall for ROB approach embankment is analysed to determine the possible cause of distress in the structure.

There are many types of rigid retaining walls like gravity retaining wall, semi gravity retaining wall, cantilever retaining wall and counter fort/buttressed retaining wall. However, the use of cantilever retaining wall in road approaches is popular with some road construction authorities and agencies due to its simplicity in design and execution. In classical conventional methods the stability of retaining wall is checked for four prominent failure modes like overturning, sliding, basal heave and drainage requirements behind the wall.

2 LITERATURE REVIEW

Previous studies done by researchers (Clough and Duncan, 1971, Anthony, 1993) on retaining wall analysis using finite element analysis indicated that horizontal earth pressures acting on the wall are in excess of the active earth pressures and also highlighted the importance of taking into account the wall movement in designing the retaining wall. In literature the failure of many retaining walls are reported and are attributed to due to improper selection of backfill in the retaining wall, temporary rise of pore water pressures due excess rainfall in the active zone increasing loading on the wall and causing the wall to translation or rotation etc. Some of the common causes of failure are long term increase in pressure of back fill, cyclic

freeze-thaw pressures, water pressure behind retaining wall, compaction pressure. Most of the failures of retaining wall occurred when the back fill is clay. Clean, free draining, granular sand or granular gravel is recommended as a back fill material. In clayey backfill, swelling pressures, high pore water pressures may substantially increase the thrust on the wall and tends to the failure of the structure. Marsh et al. (1996) reported that many cases of distress in retaining wall occurred because the walls were constructed outside the design criteria. He also reported that the retaining wall ceases to perform the intended use as design soil parameters obtained during preliminary soil investigation could be different from the values the time of construction. Robert day (1997) presented two case studies of retaining wall failures. For the first case the retaining wall failed as a result of a reduction in the lateral support. In the second case, the wall was damaged as a result of the increase in the lateral pressure from the earthquake. The above suggest the importance of considering the deformation behaviour of retaining wall using finite element analysis while designing a structure to perform its function over life of the structure using the parameters that are representative of the field conditions. Many researchers studied the failure mechanisms of mechanically stabilized walls (Jason et al. 2012, Hossin et al. 2011, Scarborough (2005)).

However, there are limited studied on the forensic geotechnical investigation of cantilever retaining wall and this paper highlights the forensic geotechnical investigation of cantilever retaining wall to determine the possible causes for the distress in the structure. It also presents the importance of using finite element analysis with consideration of deformation behaviour while designing cantilever retaining wall. Forensic geotechnical investigation of retaining walls that were constructed for a bypass road project in India is presented. Extensive geotechnical soil investigation and field measurements of distress are collected. Geotechnical soil investigations are performed on eight bore holes along the center line of the approach road. The paper presents prominent causes of failure of cantilever retaining wall using forensic geotechnical investigation. Back analysis of the cantilever retaining wall is performed using classical conventional methods and finite elements analysis.

3 DISTRESS PATTERNS

The distresses observed in the field are in the form of lateral movements, vertical settlements and rotations. However, the cantilever retaining wall made of concrete showed no sign of distress or cracks and acted like a rigid structure. The magnitudes of distress

Fig. 1. Distress patterns of retaining wall on the left and right side of east end.

Fig. 2. Distress patterns of retaining wall on the left and right side of east end.

Fig. 3. Maximum lateral displacement of wall.

Fig. 4. Distress on the flexible pavement surface.

patterns of tilt and settlements along the approach road are shown in Figures 1 and 2. From Figures 1 and 2, it is observed that the lateral displacement of the wall increases as the height of the wall increases. A maximum lateral displacement of 630mm is observed on the right of east side at 1+208.7 chainage as shown in Figure 3. Figure 4 shows visual cracks (more than 60mm wide) on the flexible pavement due to the excessive lateral displacement and vertical settlement of the embankment fill beneath the flexible pavement. Figures 5 and 6 show the vertical settlement of the pavement measured with respect to final road level (FRL) on east and west side respectively. From field measurements of vertical displacement, it is observed that a maximum of 508 mm is observed at chainage 1+397.9 on the west side. The structure showed clear signs of distress immediately after completion and hence could not be opened for traffic.

4 COLLECTION AND INTERPRETATION OF TEST DATA

This section describes the initial stage of forensic geotechnical investigation. This stage allows identifying the causes of failure or distress in a structure. In order to carry out back analysis of distressed retaining wall, information is required on the design parameters as well as distress. For this essential data is required for the analysis which depends on the amount of distress observed from the field observations. From the amount of field observations of lateral displacements and settlement of the cantilever retaining wall it is noted that the maximum observed values of distress are located near both sides of the bye pass bridge as shown in Figures 1 and 2. So, the spacing between the boreholes varied from a minimum of 54 m near to bypass bridge to a maximum of 140 m at either ends. Geotechnical properties are determined from eight boreholes along the centre line of the approach road starting from chainage 1+8.4 at east end to chainage 1+688.4 at west end. Extensive geotechnical soil investigation and field measurements of distress are collected. Standard penetration tests, classification tests, grain size distribution tests were performed on the samples collected from eight bore holes. All the boreholes were bored using conventional rotary drilling rigs. Soil samples were collected at every 1.5m depth of boring. Both disturbed and undisturbed samples were collected from each bore hole. The SPT-samples collected were used as disturbed soil samples. These samples were used for visual and physical identification and for conducting laboratory classification tests. Representative undisturbed samples were collected at depth intervals indicated in Table 1. Values of SPT N value (see Table 2) for all bore holes greater than 100 are reported as 100. These samples were used to determine bulk densities, cohesion and angle of friction

Fig. 5. Vertical settlement on east side wrt to FRL.

Fig. 6. Vertical settlement on west side wrt to FRL.

using direct shear test. Summary of soil data of cohesion, angle of internal friction, bulk density and SPT N60 value of the backfill and foundation soil from eight boreholes with depth from FRL is tabulated in Tables 1 and 2. From the grain size distribution the embankment fill have the properties of silty sand in majority of the portion of the back fill and foundation soil. Tables 3 and 4 show the limits of the gradation of the backfill material according to FHWA and TxDOT guidelines. Natural moisture content is determined from the samples collected from eight bore holes. From the observation of the variation of natural moisture content in the eight bore holes, it is observed that natural moisture content varies from a minimum of 10 % to maximum 18%.

5 BACK ANALYSIS

Back analysis provides a means to analyse the failures that frequently occurs in various technical fields including geotechnical engineering. It is of prime importance that back analysis must represent the in situ conditions to the extent possible. Choice of back analysis methodology must be based on the technical inputs and data available from the failure site and detailed laboratory investigations. Back analysis were conducted on distressed retaining wall using conventional methods and by performing rigorous finite

Table 1. Borehole log data

S. No.	Borehole No.	Depth of sample (m)	Cohesion (kPa)	Angle of internal friction (degrees)	Bulk density (kN/m^3)
1.	BH-01	1.5	-	-	21.7
		3.0	-	-	23.0
		4.5	-	-	25.0
		6.0	-	-	22.2
		9.0	-	-	22.4
2.	BH-02	1.5	14.0	20.2	19.4
		3.0	-	-	20.7
		4.5	-	-	21.4
		6.0	-	-	20.8
		9.0	-	-	22.3
2.	BH-02	10.5	-	-	21.7
		12.0	-	-	22.2
		13.5	-	-	22.5
3.	BH-03	1.5	5.0	23.0	18.8
		3.0	10.0	30.2	19.6
		4.5	10.0	32.0	19.6
		6.0	-	-	19.6
		7.5	-	-	20.4
		12.0	-	-	22.2
		13.5	-	-	20.5
		15.0	-	-	21.9
		16.5	-	-	19.6
		18.0	-	-	22.2
4.	BH-04	1.5	6.0	27.0	18.4
		3.0	12.0	28.90	18.9
		4.5	12.0	30.30	18.9
		6.0	15.0	29.00	18.9
		7.5	-	32.20	19.5
		9.0	16.0	31.00	19.5
		12.0	15.0	22.00	19.9
		15.0	-	-	20.9
		16.5	-	-	21.40
		18.0	-	-	21.4
5.	BH-05	1.5	4.0	23.4	18.7
		3.0	7.0	30.3	19.4
		4.5	12.0	31.00	20.7
		6.0	-	-	21.2
		7.5	15.0	32.00	19.8
		9.0	14.0	30.30	19.9
		10.5	22.0	30.30	29.9
		12.0	20.0	31.00	18.9
		13.5	-	-	21.6
		15.0	-	-	20.9
6.	BH-06	18.0	-	-	21.9
		19.5	-	-	20.9
		1.5	4.0	22.30	18.9
		3.0	12.0	27.30	19.6
		4.5	-	-	21.2
		7.5	-	30.30	20.20
		9.0	-	-	21.9
		10.5	-	-	19.6
		13.5	-	-	22.2
		15.0	-	-	22.2
7.	BH-07	16.5	-	-	22.4
		1.5	5.0	31.3	19.4
		3.0	-	-	20.4
7.	BH-07	6.0	-	-	20.9
		9.0	-	-	22.2
		10.5	-	-	22.5
8.	BH-08	16.0	-	-	21.4
		1.5	18.0	29.3	19.9
		3.0	-	-	20.2
		4.5	-	-	20.4
		10.5	-	-	22.2

element analysis using a computational code (Plaxis V8). Various section of retaining wall with different heights (11.18m and 12.4m) at chainages 1+228.7 and 1+397.47 were analysed independently. Section 1(11.0m height of wall) has lateral displacement of 380 mm and vertical settlement of 327 mm as shown in Figures 1 and 5. Section 2 (12.4 m height of wall) has horizontal tilt of 280 mm and maximum vertical tilt of 508mm at the center as shown in Figures 2 and 6. The

Table 2. SPT N60 Values.

Depth of sample below FRL (m)	BH-01	BH-02	BH-03	BH-04	BH-05	BH-06	BH-07	BH-08
2	68	24	9	26	8	11	59	37
3.5	100	76	16	13	18	55	32	45
5	30	100	38	14	36	53	51	34
6.5	100	20	65	26	38	15	42	88
8	100	100	41	29	16	100	29	100
9.5	100	44	32	17	16	26	100	100
11	100	60	100	19	11	69	69	-
12.5	-	100	61	54	100	100	100	-
14.0	-	100	48	61	48	81	100	-
15.5	-	100	100	63	81	100	100	-
17.0	-	-	77	100	100	100	-	-

Table 3. Gradation limit of backfill (FHWA).

U. S Sieve Size	Percent Passing
102 mm (4 in.)	100
0.425 mm (No 40)	0-60
0.075 mm (No 200)	0-15
Plasticity index should not exceed 6%	

Table 4. Gradation limit of backfill (TxDOT).

Type A		Type B	
Sieve Size	Percent Passing	Sieve Size	Percent Passing
76 mm (3 in)	100	152 mm (6 in)	100
0.425 mm (No. 40)	0-60	76 mm (3 in)	75-100
0.075 mm (No 200)	0-15	0.075 mm (No 200)	0-15
Plasticity index should not exceed 6%			

following section presents the result of the analysis from conventional analysis and numerical analysis.

6 CONVENTIONAL ANALYSIS

The stability checks of cantilever retaining wall include overturning about the toe, condition of no tension at the base, sliding stability, maximum pressure on the foundation soil and other checks. For the present case two sections (section 1 & section 2) stability of the retaining wall is determined with respect to overturning, sliding and basal heave. The results of the stability checks for section 1 and 2 are presented in this section. For section 1, the height of the wall is 11.18 m with base width of 8 m and a thickness of 0.3 m of stem as the top width. For section 2 the height of the wall is 12.4m with base width of 8.5 m and a thickness of 0.3 m of stem as the top width. The geometry of the section 1 and section 2 are at chainages 1+228.7 and 1+397.47 on the east end and west end respectively are shown in Figures 7 and 8. The cantilever retaining wall is constructed with concrete of unit weight 25kN/m^3 . Figures 9 shows the prescriptive dimensions of the cantilever retaining wall given in Chen (1995) and Das (2002) followed in general in many countries. From the observations of the dimensions, it is noted that section 1 & 2 follow the prescriptive guide lines for the retaining wall designs.

The soil properties of BH-03 which is close to the chainge 1+228.7for section 1 and BH-05 for section 2 are considered for the analysis. The average soil properties considered for the analysis for backfill and foundation soil are presented in Table 7 and 8. From the grain size analysis the embankment fill is classified as silty sand. Silty sands will have higher Poisson's ratio

Fig. 7. Geometry of section 1 at chainage 1+228.7.

Fig. 8. Geometry of section 2 at 1+397.47.

Fig. 9. Prescriptive cantilever wall dimensions

(0.3-0.35) when compared to sands and gravel. The low modulus of elasticity and high Poisson's ratio allows the backfill to deform higher than the required to develop active pressures compared to clean sands and gravels. From the results of the conventional methods presented in Table 5, it is observed that the safety factors with respect to overturning and basal heave are higher than the critical values specified for section 1 and section 2. However, the safety factor with respect to sliding stability is less than the critical factor of safety 1.5. From the above it is evident that the retaining wall will suffer excessive lateral displacement due to failure with respect to sliding stability. However from the field observation a tilt with combination of

Table 5. Results from conventional analysis.

Failure Mode	Section 1	Section 2	Required minimum safety factor
Overturning about toe	3.6	3.95	2.0
Sliding Stability	1.0	1.05	1.5
Basal heave failure	6.4	5.36	3.0

Table 6. Concrete properties

Parameter	Value
Material model	Linear elastic
Unit weight, γ_c	25.0 kN/m ³
Elasticity modulus, E_c	40 MPa
Poisson's ratio, ν	0.15

Table 7. Properties of backfill soil.

Parameter	Name	Section 1	Section 2
Material Model	Model	Mohr - Coulomb	Mohr - Coulomb
Type of Material Behavior	Type	Drained	Drained
Unit Weight	γ_{unsat}	20.03 kN/m ³	21.1kN/m ³
Saturated Unit Weight	γ_{sat}	21 kN/m ³	22 kN/m ³
Horizontal Permeability	k_x	1.0m/day	1.0m/day
Vertical Permeability	k_y	1.0m/day	1.0m/day
Young's Modulus	E_{ref}	15MPa	11MPa
Poisson's Ratio	ν	0.3	0.3
Cohesion	c_{ref}	2.0 kPa	2.0 kPa
Friction Angle	Φ	28.4	29.75

Table 8. Properties of foundation soil.

Parameter	Name	Section 1	Section 2
Material Model	Model	Mohr - Coulomb	Mohr - Coulomb
Type of Material Behavior	Type	Drained	Drained
Unit Weight	γ_{unsat}	21.05 kN/m ³	21.3kN/m ³
Saturated Unit Weight	γ_{sat}	21 kN/m ³	22 kN/m ³
Horizontal Permeability	k_x	1.0m/day	1.0m/day
Vertical Permeability	k_y	1.0m/day	1.0m/day
Young's Modulus	E_{ref}	42 MPa	27MPa
Poisson's Ratio	ν	0.3	0.3
Cohesion	c_{ref}	2.0 kPa	2.0 kPa
Friction Angle	Φ	28.4	29.75

vertical settlement of the backfill and rotation of the retaining wall is observed. This shows that the distress in the cantilever retaining wall is a combination of failure mechanisms which contains horizontal tilt, translation and rotation of the cantilever retaining wall. The stability of the retaining wall with respect to overturning does not consider the deformation of the backfill and the wall which develops higher earth pressures than the earth pressures for vertical wall. This shows that the classical conventional method cannot be applied to predict the actual failure modes.

7 NUMERICAL ANALYSIS

Two sections of cantilever retaining wall with design height (11.18 m and 12.4 m) were simulated using finite element computational code (plaxis V8). The mohr coulomb constitutive model was used to represent backfill and foundation soil behaviour. Fifteen noded triangular elements with very fine mesh density were used to discretise the soil domain. An overall fineness set to very fine may be used provided the computing machine is capable of handling such simulations without significantly affecting the speed of calculation. Concrete wall is modelled as linear elastic and non-porous material type. The unit weight of the concrete is set as 25 kN/m³. Typical material properties for concrete are presented in Table 6. For section 1 and section 2, the average soil properties for backfill material and foundation soil are taken from Table 1. The properties of the backfill material and foundation soil for section 1 and section 2 are presented in Tables 7 and 8. The results of the finite element analysis for sections 1 & 2 are presented in Tables 9 and 10. From Tables 9 and 10, it is observed that the global factor of safety using phi-c reduction technique is less than 1. The deformations measured in the field are in good agreement with finite element results. Although conventional analysis for section 1 and 2 show that the safety factor for over turning and basal heave are greater than the critical safety factor, failure occurred as a combination of overturning and sliding. Back analysis of failure showed that the mechanism of failure is a combination of sliding and overturning and the deformations are in conformity with the predictions obtained from the numerical analysis. This can be better represented by the global safety factor which considers the deformation behaviour of the soil to calculate the global safety factor.

Table 9. Results of numerical modelling for section 1.

Parameter	Section 1	Field measurement
Global factor of safety	0.4	-
Lateral displacement (mm)	342	380
Vertical settlement (mm)	342	327

Table 10. Results of numerical modelling for section 2.

Parameter	Section 2	Field Measurement
Global factor of safety	0.34	-
Lateral displacement (mm)	300	280
Vertical settlement (mm)	600	508

8 CONCLUSIONS

This paper presents the results of forensic geotechnical investigation of a distressed cantilever retaining wall for ROB approach embankment. From the results of the conventional analysis and finite element analysis, it is observed the retaining wall designs based on prescriptive guidelines may not lead to satisfactory designs and considerations of deformations is important. Back analysis of failure showed that the mechanism of failure is a combination of sliding and overturning and the deformations are in conformity with the predictions obtained from the numerical analysis.

REFERENCES

- 1) Anthony, T. C. Goh (1993). Behaviour of cantilever retaining walls, *Journal of Geotechnical Engineering*. 19(11), 1751-1770.
- 2) Braja M. Das (2002). Principles of geotechnical engineering, 7th ED., Cengage Learning.
- 3) Clough, G. W. & Duncan, J. M. (1971). Finite element analysis of retaining wall behaviour. *Journal of Soil Mechanics and Foundations*, ASCE, 97(12), 1657-1673.
- 4) Hossain, M. S. Kibria, G. , Khan, M. S. , Hossain, J. and Taufiq, T. (2011). Effect of backfill soil on excessive movement of MSE wall. *Journal of Performance of Constructed Facilities*, in press.
- 5) Jason Y. Wu., P. E., M. and Nelson N. Chou. (2012). Forensic studies of geosynthetic Reinforced Structure failures. *Journal of Performance of Constructed Facilities*, in press.
- 6) Scarborough, J. A. (2005). A tale of two walls: Case histories of failed MSE walls. *Proc., Slopes and Retaining Structures under Seismic and Static Conditions*, GSP 140, Geo-Frontiers 2005, ASCE, Reston, VA.
- 7) T. Marsh & Richard, K. Walsh. (1996). Common causes of retaining-wall distress: case study. *Journal of Performance of Constructed Facilities*, 10(1), 35-38.
- 8) W. F. Chen (1995). The civil engineering handbook, CRC Press, Inc. Robert, W. Day. (1997). Design and construction of cantilevered retaining walls. *Practice periodical on structural design and construction*, 2(1), 16-21.