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Short Communication
(Kısa Makale)

Retaining Wall Failure due to Poor Construction and Design Aspects A Case Study:

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Abstract

A retaining wall which is the subject of this paper collapsed without any indication on May 25, 2006 at city center of Kahramanmaras, Turkey. While there were no life losses, a building was severely deformed and damaged. Just after the failure of the retaining wall an investigation carried out locally provided relevant results concerning the quality of the materials used in the construction of the wall. Detailing the reinforcement is crucial in reinforced concrete structure as it affects the rigidity of the structure. The consequent studies have shown that the failure has taken place primarily due to low material quality and poor workmanship. There was also design of project errors. Furthermore, the design and construction were not made in accordance with the TS 7984 Turkish standard.

Key Words: Retaining Wall, Failure Analysis, Poor Construction and Design

Özet

Bu çalışmanın konusu 25 Mayıs 2006'da Türkiye'de, Kahramanmaraş şehir merkezinde, hiçbir belirti göstermeksizin yıkılan bir istinat duvarıdır. İnsan kaybı yaşanmazken, yakındaki bir bina ağır bir şekilde hasar görmüştür. İstinat duvarının yıkılmasının hemen ardından yapılan araştırmalar duvarın inşasından kullanılan malzemelerin kalitesini de içeren ilgili sonuçları sağlamıştır. Takip eden çalışmalar yıkılmanın öncelikle düşük malzeme kalitesi ve kötü işçilikle ilgili olduğunu göstermiştir. Bazı proje hataları da mevcuttur. Ayrıca, yapının tasarımı TS 7984 e göre uygun bir biçimde yapılmamıştır.

Anahtar Kelimeler: İstinat Duvarı, Hasar Analizi, Kötü İşçilik

1. INTRODUCTION

The retaining walls (RW) are constructed for holding back soil from a building, structure or area. The main objective of these structures commonly constructed using masonry, stone, brick and concrete is to prevent down slope movement of soil or to resist the lateral pressure acted by soil [1-2]. However many retaining walls may fail due to the poor-design, poor materials and installation with insufficient numbers of support to keep the wall from moving. Three main checking are necessary for the design of the RW which are overturning, sliding and bearing capacity [3]. The other important consideration for the RW is the water table which has significant effects on the lateral pressure. The water pressure due to water table reduces the effective stresses which are advantages for stabilization of RW; it acts as additional pressures to wall which forces to RW for overturn and sliding [4-5].

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The contractor should be questioned why RW walls fail in spite of conservative design measurers. However, many RW failures have taken place as results of many factors such as poor construction, poor engineering, inferior quality materials, unexpected conditions lack of coordination of responsibilities between the owners and the design consultants [6-9].

This paper focuses on a failure of a RW in Kahramanmaras, Turkey. It appears that the failure occurred principally due to poor engineering, the use of low quality materials and poor workmanship. The lessons learned from reviewing of the causes of RW failure are reported here.

2. BACKGROUND

2.1 RW Performance

The failure was occurred in May 2006. The primary reason for the failure seems height of the wall (8.9 m) and the development of water pressure due to a heavy rain behind the wall which has not draining system. On the other hand the additional surcharge loading is not taken into consideration for the design such as weight of the vehicles parking above the wall. Some heavily damaged patterns of the collapsed building and the RW can be seen in Figs. 1-3. The failure occurred in some sections of the wall and start the bottom of the foundation and upper section of RW were suffered from failure. This failure occurred during or shortly after significant rainfall induced. Pore water pressure appeared to be the trigger for this failure. Observations after the failure revealed some evidence of seepage erosion or water movement at the soil face. The near vertical face appeared to consist of uniformly damp relatively undisturbed aggregates. A few days after the failure, a heavy rain caused water flow out of the pavement base course at the collapsed section of the wall.

Fig. 1. Retaining wall failure

Fig. 2. Collapsed retaining wall

Fig. 3. Severe damage of the building knocked by the retaining wall

2.2 Details and Design Errors

Analyses for concrete thickness and steel bar of RW were performed according to Turkish standard TS 7994 [18]. The result of the analyses showed that a number of detailing deficiencies were observed in the damaged buildings. This failure seems to be due to insufficient dimensional stability of the RW from the figure below.

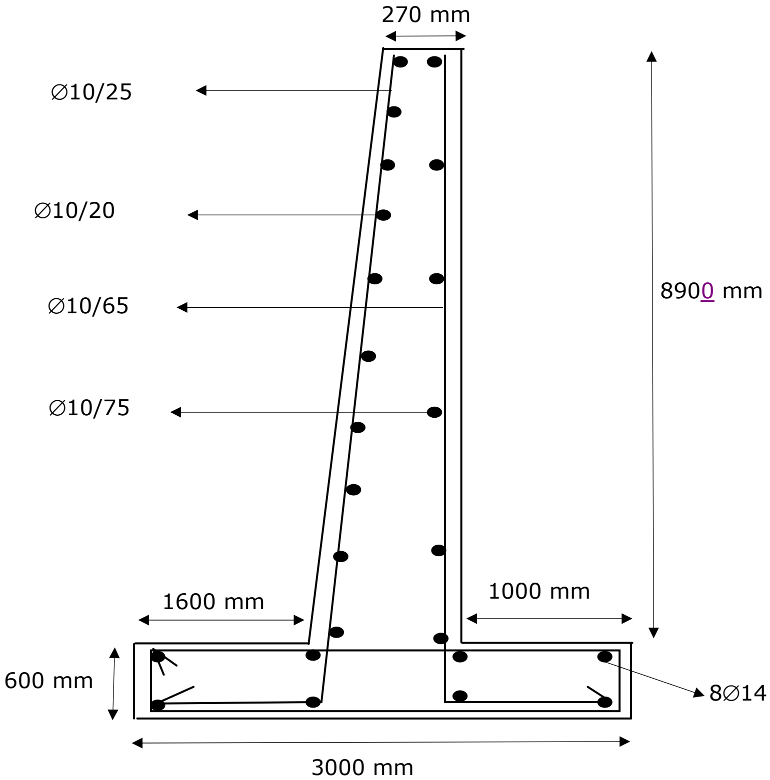


Fig. 4. Section of damaged RW

2.3 Effects of Material Properties

In this case study, low material quality is considered to be one of the causes of the damage. The poor concrete quality and poor design despite the requirements of the code are the real causes of destruction. Moreover, the concrete segregations were observed (Fig. 5.) and the aggregates had bad particle size distribution (Fig. 6.). Particle size distribution of aggregates used is given in Fig 7. The aggregates had been taken from a dry river bed very near to the site and included a high percentage of organic materials. Compressive strengths of RW concrete and damaged building (with hammer test and Core tests) are given in Table 1. Reinforcement detailing is crucial in RC structure as it affects the rigidity of the structure. The poor concrete quality and poor design despite the requirements of the code are the real causes of destruction.

Fig. 5. Segregated concrete of the RW

Fig.6. Aggregates with no particular particle size distribution

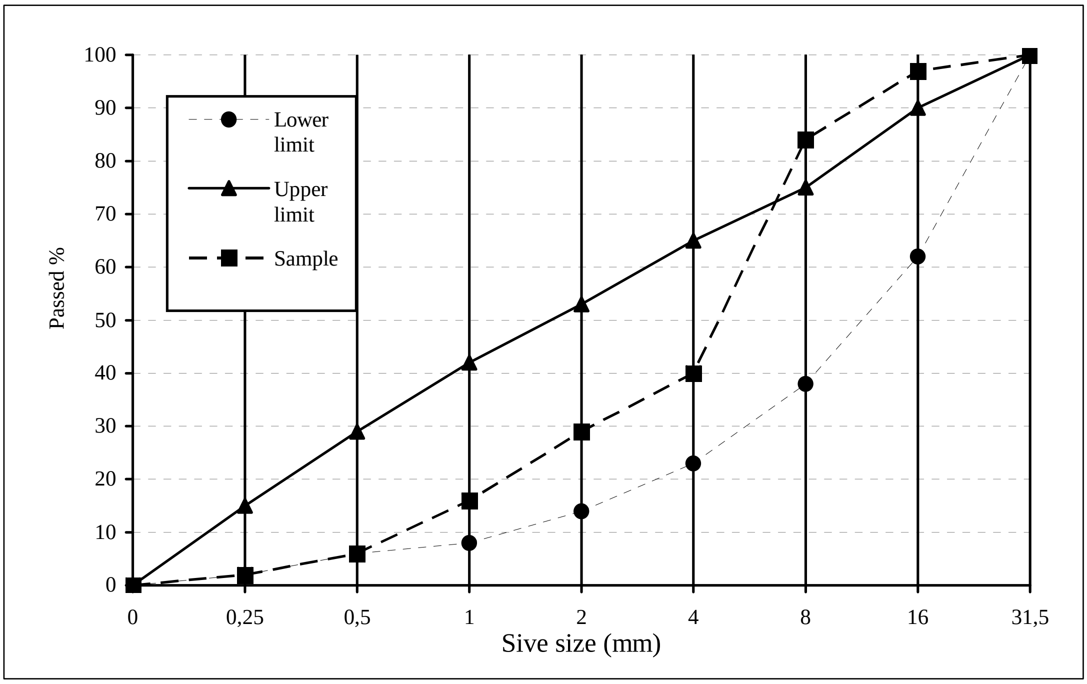


Fig. 7. Particle size distribution of aggregates used for RW along with upper gradation limits.

Table 1. Compressive strengths of RW concrete and damaged building

(With Hammer and Carrot tests, averages of three samples)

Concrete	Core test (MPa)	Carrot test (MPa)
RW	14.4	13.2
Damaged building	21.3	20.9

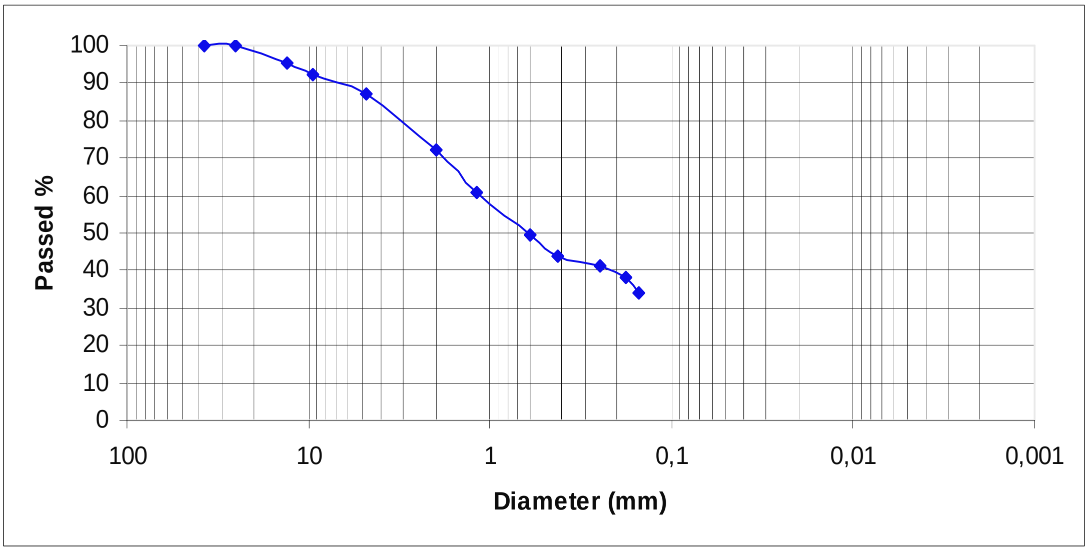
2.4 Design Concerns

The project was not designed considering the TS 7994 [10] standards and provisions. This standard included that Eurocode 8- Design of structures for earthquake resistance-Part 5: Foundations, retaining structures and geotechnical aspects. In this standard, materials quality and design of RW criteria are given. According to TS 7994 [10], in the designing of retaining walls, the stability against overturning, sliding, excessive foundation pressure and water uplift must be explored. The safety factor for the gravity walls must be at least 2 and minimal wall thickness must be 50 cm. The lateral pressures acting on walls are calculated according to Coulomb Theory. This theory suggests that the failure surface is a plane and the friction between soil and wall is taken in to consideration. TS 7994 [10] also requires the total failure analysis against the possibility of the failure of the walls together with soil. For that purpose, stability analysis is performed using simple slice method of which detail is given in TS 7994.

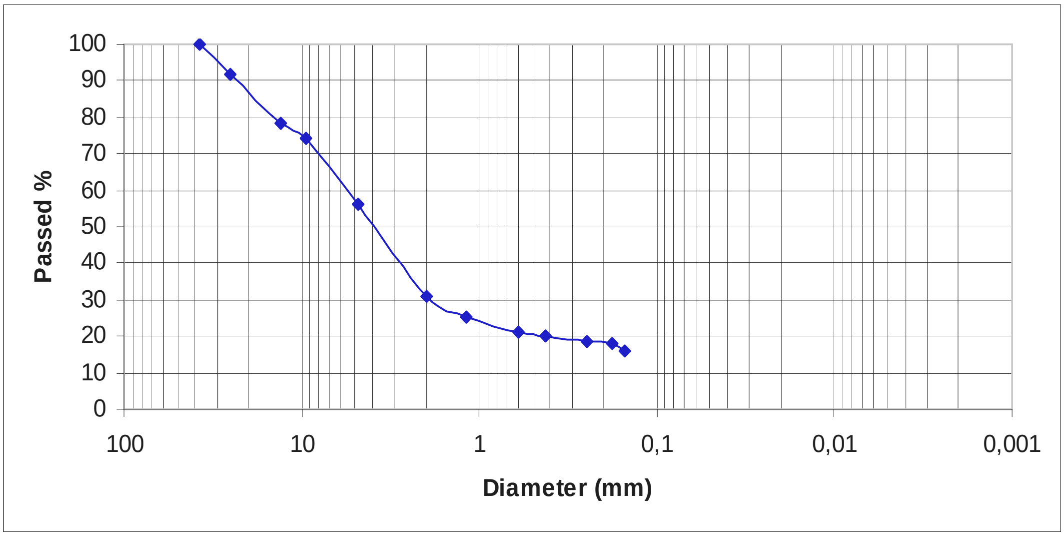
3. FAILURE INVESTIGATION

3.1 Soil Properties

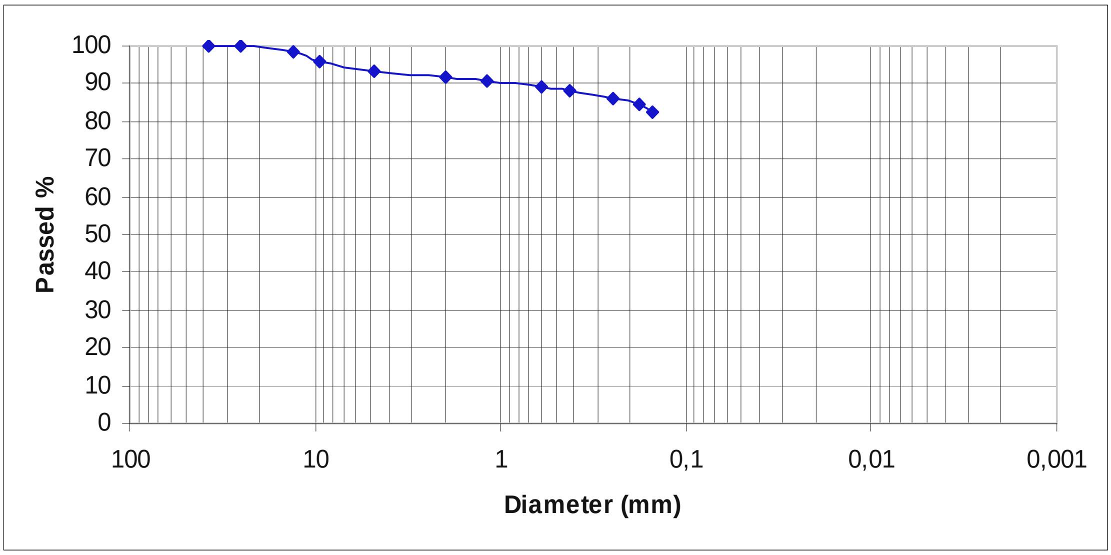
The physical and mechanical properties of soil were examined. For this purpose, the undisturbed and disturbed soil samples were taken by drilling from dept changing from 3 to 10 meters. Samples were carefully extracted from the boreholes to perform the standard geotechnical tests in the laboratory such as Atterberg limits and unconfining compression test. The Grain size distribution curve of soil is plotted in Fig. 8.



Depth =3 m



Depth=6 m



Depth=10 m

Fig. 8. The typical gradations of the site soils from different depths

In order to determine the causes that led to the failure of the RW an investigation was carried out on the materials on which the foundations were built. The material on which the footing of RW rested is made up of silt gravel (GM). Accordingly, a series of geotechnical tests were carried out both in situ and in the laboratory. These tests included: water content, Atterberg Limits, soil classification and standard penetration tests (SPT). The in-situ tests comprised SPT to determine the load bearing capacity of the ground. The laboratory tests carried out on the soil focused on determining the strength characteristics of the soil present in the area. For this purpose a series of simple compression strength tests were performed.

3.2 RW Design

The wall was designed using a vendor developed software program which generally followed the Turkish National Concrete Design Methodology for internal and external stability. Geometrical description of the wall is given in Fig. 9. The compacting soil parameters used in the design of the RW were provided by the soil tests and are given in Table 2. The wall was designed assuming water or hydrostatic pressure would be present within the soil. Partitioning of the cross-section of the cantilever wall into simple geometrical pieces is given in Fig. 10(a) and 10(b). The estimated permeability of the compacted glacial till was 10.4–10.5 cm/s. A typical cross-section of the wall consisted of primary reinforcement steel mesh with 8mm diameter.

Table 2. The parameters of compacting soil used behind the RW

Water absorption	Consistency limit	Plasticity index	Soil classification (USCS)
%9	NP	NP	GM

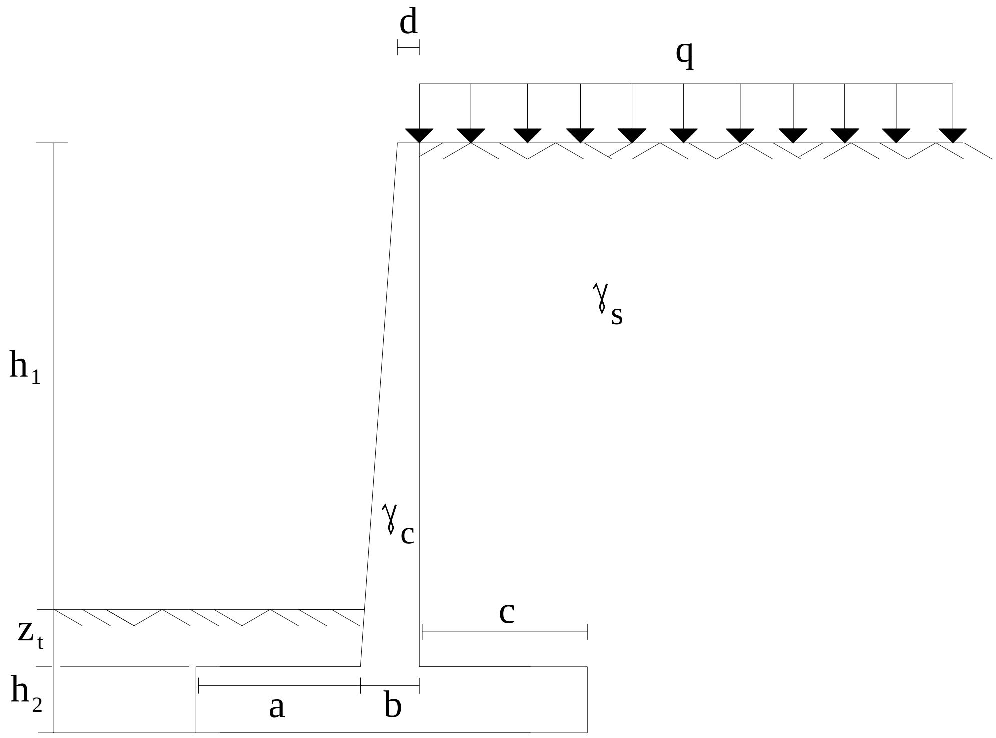


Fig. 9. Geometrical description of the wall

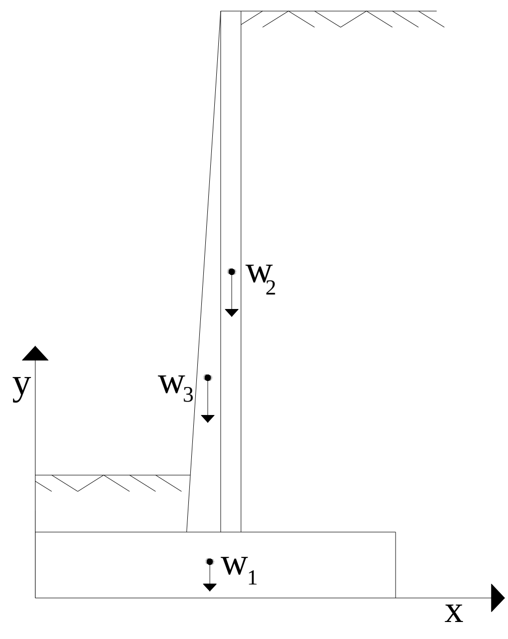


Fig. 10 (a). Concrete weights of different sections of the RW

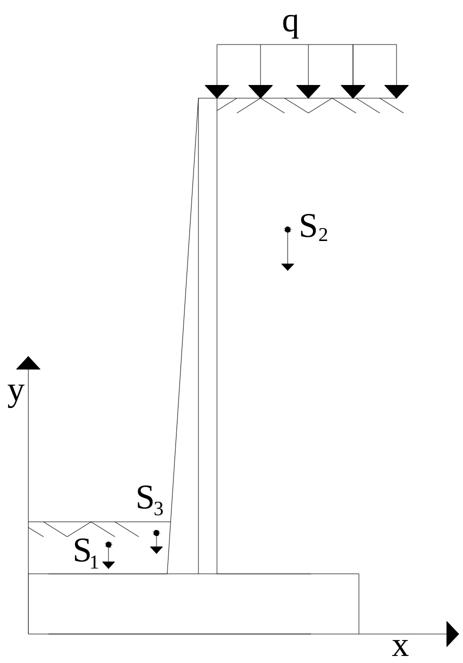


Fig. 10 (b). Soil weights on different sections

A review of the original design was performed using the Turkish Concrete Masonry Association Design Guidelines [11]. Internal and external facing stability and global stability of RW were evaluated. A retaining wall problem involves many variables, such as wall dimensions, backfill slope, concrete and steel strengths, allowable soil bearing capacity, backfill properties and water table level, etc. The original design was based on the assumption that no hydrostatic pressure would be acting on the RW. Connection strength properties between the RW units and foundation were based on laboratory tests provided by the manufacturer. The design section presented here is for the highest section of the wall measuring 8.9 m in height from leveling ground to the top of the wall. The foundation, connecting beam and RW width are 35, 40 and 27 cm, respectively. Poor bonding between concrete and steel hooks of stirrups were not curled into the concrete core and inadequate clear cover can cause corrosion of steel [12-13]. In this study it is examined that inadequate compressive strength, poor particle size distribution, inadequate reinforcement and poor connection concrete and rebars are determined. Also, core thickness and transverse reinforcement were not enough.

3.3 Definition of RW

Geometry of the wall is defined in Figs. 10 and 11. The main elements used in the wall design are geometric, acting forces and material properties data. These data are h_1: height of the wall, q: surcharge, γ_c: unit weight of the concrete, γ_s: unit weight of the soil, k_a: active pressure coefficient, k_p: passive pressure coefficient, σ_s: soil strength and Pw : water pressure.

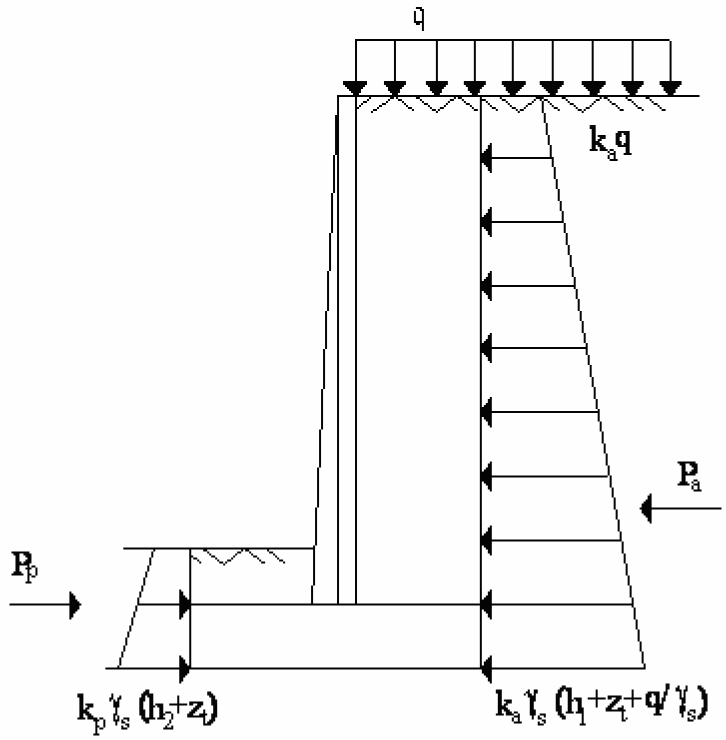


Fig. 11. Illustration of the earth pressures on both sides of the wall

3.3.1 Forces on the Design

Before the analyses of RW stability, the total weight of the wall, soil and the earth pressures acting on the wall with the corresponding points of application are determined. Then the constraints are established. For this purpose, intermediate or auxiliary variables that facilitate the work can be used. Since the formulations allow the use of these auxiliary variables, an explicit expression for the constraints in terms of the design variables is not needed (formulas 1 and 2). Fig.12 illustrates the weights, w_i; i=1, 2, 3, of the different pieces of the wall and their positions. Similarly, the weights, s_i; i=1, 2, 3, of the different pieces of the soil are illustrated in the same Figure. Illustration of the earth pressures on both sides of the wall is given in Fig. 11. Calculation of the pressures and weights are given in Fig. 12.

The dimensions of the wall are as follows: a=160 cm, b=40 cm, c=100 cm, d=27 cm, Zt=30 cm, q=1.7 t/m^3, h_1=890 cm, h_2=35 cm, γ_c=24 kN/m^3 and γ_s=17.8 kN/m^3 (see Fig. 7). The internal friction angle for the soil (GM) behind the RW is ϕ=35^o.The design dimensions of the wall are determined and the necessary calculations are made (see Fig.11). The active and passive lateral soil pressures obtained using equations (1) and (2), via Rankine Method, are given in Table 3. The pressure forces, weights and moments calculated are given in Table 4.

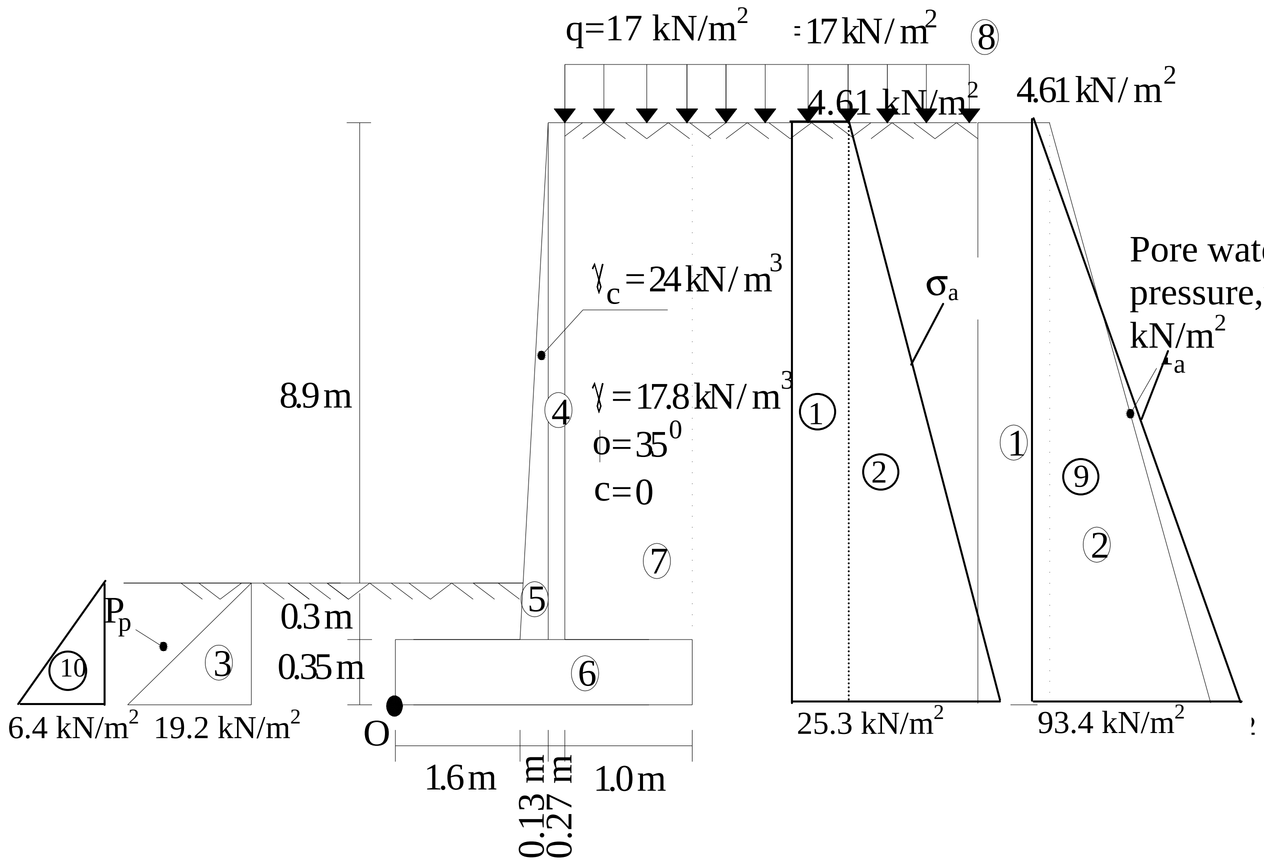


Fig. 12. Illustration of the calculation of the pressures and weights

Table 3. Active and passive lateral pressure values

Active lateral pressure values						Passive lateral pressure values					
Depth (m)	Pore water Pressure (u) (kN/m^2)	Total Vertical Stress (σ_v) (kN/m^2)	Effective Vertical Stress (σ_v) (kN/m^2)	K_a	Active Lateral Pressure σ_a (kN/m^2)	Depth (m)	Pore water Pressure (u) (kN/m^2)	Total Vertical Stress (σ_v) (kN/m^2)	Effective Vertical Stress (σ_v) (kN/m^2)	K_P	Passive Lateral Pressure σ_P (kN/m^2)
0.0	0	17.0	17	0.271	4.61	0	0	0	0	3.69	0
9,55	93.4	186.9	93,6	0.271	25.3	0.65	6.37	11.57	5.2	3.69	19.2

Table 4. Pressure forces and their moments

Load number	Force or weight (kN)	Moment arm (m)	Moment (kNm)
1	4.61×9.55 = 44.03	4.77	210.02 (+)
2	(25.3–4.61)×9.55/2 = 98.8	3.18	314.3 (+)
3	19.2×0.65/2 = 6.24	0.22	1.4 (-)
4	0.27×9.2×24 = 59.62	1.865	111.19 (-)
5	0.13×9.2×24/2 = 14.35	1.686	24.19 (-)
6	0.35×3.0×24 = 25.2	1.5	37.8 (-)
7	1.0×9.2×17.8 = 163.76	2.5	409.4 (-)
8	1.0×17 = 17	2.5	42.5(-)
9	93.4××9.55/2 =446.9	3.18	1422.6 (+)
10	6.4×0.65/2 =2.1	0.22	0.45 (-)

$p_a = (\sigma_v\text{-}u)K_a$, $K_a = tg^2(45 - 35/2) = 0271$, $\sigma_v = q + \gamma z$ (1)
$p_p = (\sigma_v\text{-}u)K_p$, $K_p = tg^2(45 + 35/2) = 3.69$, $\sigma_v = q + \gamma z$ (2)
$(\sigma_v\text{-}u)$= Effective presure, K_a= Coefficient of active earth pressure, K_p= Coefficient of passive earth pressure , γ= unit weight of soil

In case ground water exists in the soil, the effective stresses in soil decrease due to the water pressure. This leads a decrease in active and passive pressure acting on RW. The other effect of ground water is that the hydrostatic pressure developes behind the RW. The hydrostatic pressures must be added to lateral earth pressures.

For the RW investigated herein, horizontal and vertical forces and moments are computed. While the overturning moment is calculated as 1946.9 kNm, the resisting moment is founded as 629.9 kNm. These calculation shows that the overturning safety factor which is the ratio of the resisting moment to the overturning moment for the RW is 0.32. Whereas the safety factor should be at least 2 according to CE-TS EN ISO 9001:2000.

On the other hand, the sliding check is performed. For that purpose total lateral force is calculated as 581 kN/m. considering total vertical force which computed as 280 kN/m, the friction force between the foundation of RW and soil is calculated as 118.8 kN/m. In this circumstance the safety factor for sliding is found as 0.2. This low value indicates that the RW is unsafe against the sliding. It should be at least 1.5 according to CE-TS EN ISO 9001:2000.

3.5 Material Properties

Poor material quality may have been one of the main factors that caused the collapse of many structures. Damage due to poor quality of material was reported many of researchers [14–17]. Ready mix concrete is relatively new for Turkey and it has become popular in Turkey. Generally, hand made concrete is used. Turkish labor bewares of the principles of quality of concrete. Lack of proper concrete mix design, lack of sieve analysis, lack of vibration during the concrete placement, insufficient curing of concrete after placement, without attention to weather conditions and high water and cement/ratio for workability are general mistakes. In this case study, similer mistakes were observed.

The compressive strength of concrete cores extracted from damaged and collapsed RW indicate significantly low strength (As seen Table 1). The quality of concrete in typical buildings is one of the major factors in the poor performance to resist strong motions.

3.6 The resons behind the failure

At the connections of beams and RW, reinforcement details are of almost relevance and some of them are listed:
- The RW is designed by ignoring the hydrostatic pressure.
-The heavy rainfall causes the water level to rise behind the RW because of insufficient drainage system.
- Construction mistakes, not obeying project of the RW
- Poor quality of concrete may have been one of the main factors that caused the collapse of RW.
- Although there are control procedures in Turkey but sometimes it is ignored. For instance dimensions of bound beam and RC bar were inadequate according to the TS EN 1998-5 and lack of transverse reinforcement at member connection was observed.

4. NUMERICAL RESULTS AND DISCUSSION

Considering the geometric properties of the retaining wall and the effect of the soil behind it, the overturning safety factor is 0.32 and the sliding safety factor is 0.2. However, for a safe design these values should be at least 2 and 1.5, respectively. The analysis shows that the RW investigated herein is unsafe both against shear force and overturning moments. The RW is probably designed by ignoring the hydrostatic pressure. The heavy rainfall causes the water level to rise behind the RW because of insufficient drainage system. The rising of the water level leads the hydrostatic pressure which is reduce the effective stresses in soil. Therefore the hydrostatic pressure must be added to lateral pressures acting on RW. A decrease in effective stresses may seem to be profitable, since the lateral stresses acting on RW reduce. However the hydrostatic pressure leads grater pressure than decrease in effective stresses. Thus, the main cause of failure of RW appears to be hydrostatic pressure as a result of heavy rainfall.

The main purpose for the construction of the retaing wall was to protect the building, however its failure caused a great risk for the lives of people living in the building as the collapse of the retaining wall caused serious damage to the building (see Fig.3). A total collapse of the retaining wall would result in considerably greater damage to the building.

5. CONCLUSIONS

The observations and findings of the current study are briefly summarized in the following.

1- The main reason of failure was that the hydrostatic pressure was not taken into consideration in the calculation of lateral pressure. The effective stress decreased as result of an increase in hydrostatic pressure developed due to the heavy rainfall and the rising water level led the additional force acting on RW.

2- The aggregate used was not clean and the cure process of concrete was not adequate and aggregate used was pit-run gravel type. Concrete used in the collapsed RW did not contain a proper crushed aggregate and it had poor adherence characteristics.

3- The quality of the concrete used in the construction of the RW was low. The compressive strength of the concrete exhibited a wide range of values (10–14 MPa). It seems that the one of reasons for the wide range of compressive strength observed was due to the hand mixing of the concrete. It is clearly stated that the concrete used in the first and second earthquake zones should be C20 or higher quality [11]. In the new earthquake code, the concrete used in this RW was found to be under C20 quality.

4- The control procedures are ignored.

5- Some important lessons for design and construction practice can be learned from damage of RW. The inadequate structural systems and members, low quality materials and inappropriate construction are main reasons of the damage. Construction of buildings to withstand similar effect can be possible if the above mistakes are stopped to be repeated. This can be achieved if engineers, architects and contractors understand of RW design and construction principles. An efficient control mechanism at any phase of concrete production and control procedures of this type of structure should be established. In this way, improved structural response of RW during future events will be achieved. An effective control mechanism is needed to prevent similar catastrophes in the future.

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