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INVESTIGATION OF STRENGTH PROPERTIES OF RANDOM RUBBLE MASONRY FOR DESIGN OPTIMIZATION

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Abstract: Presently the conventional design methods are used in the design of Random Rubble Masonry (RRM) retaining walls due to lack of knowledge on design strength properties of RRM. Use of conventional methods in design of RRM retaining walls results larger sectional areas of retaining walls which lead to higher construction costs. This paper describes the research study carried out to investigate the characteristic compressive strength, flexural strength and shear strength of RRM, which are needed for the design optimization of RRM retaining walls. Analytical study was carried out for the design optimization of a RRM retaining wall using the strength results obtained from experimental study. Further, the number of steps in the cross section of RRM wall has been varied to study the effect of variation of number of steps on design optimization. It is found that the cross-sectional area can be reduced by increasing the number of steps in the retaining wall. The reduction in the cross sectional area is not significant when the number of steps is more than three. The results show that the cross-sectional area of the RRM retaining wall can be considerably reduced by considering the flexural strength capacity of the RRM in the design.

Keywords: Compressive strength; Flexural strength; Random rubble masonry; Retaining wall; Shear strength;

1. Introduction

Random rubble masonry walls are constructed using rubble stones of random sizes and random shapes bonded together with a mortar layer. There is no exact bond pattern in this type of masonry [1]. The mason selects stones randomly to place appropriately to obtain a good bond and hence all characteristics of RRM greatly depend on the workmanship. Horizontal bed joints may form in RRM when the mason is not skilful.

Random rubble masonry has been commonly used in the past due to various advantages such as durability and common availability. At present, this type of masonry is widely used only in buildings where aesthetic appearance is important, earth retaining structures with low retaining heights and shallow foundations. Due to the lack of design data of RRM, designers are reluctant to use RRM in retaining wall with higher retaining heights.

Various types of mortar joint finishes such as flush, galetted, recessed, ribbon, v-grooved joints can be used in the RRM construction where aesthetical view is important [2]. Flush mortar joint is the most common type in structures where appearance is not important. In this study, all experiments have been carried out to determine characteristic strengths of RRM with flush joints. Cement mortar 1:5 (cement: sand) was used as it is the commonly used mortar designation for RRM industry.

The shear resistance of random rubble masonry wall is an important property for the resistance to seismic loads on buildings [3]. It is reported that the shear strength of RRM decrease with the increase of the bond randomness of masonry [3]. Shear failure modes depend on wall geometry, boundary conditions, applied axial load and material characteristics [4].

Conventional RRM earth retaining wall designs are carried out as gravity retaining walls considering the weight of the wall resisting all effects of forces induced by soil mass.

2. Experimental study

2.1 General

All RRM test specimens were constructed with locally available rubble stones and 1:5 (cement: sand) mortar designation. For mortar, ordinary portland cement and river sand were used. A thickness of 300 mm was selected for all test specimens as it is the possible minimum thickness to construct masonry wall panels using commonly available 6"-9" stones. All specimens were covered with polythene sheets to prevent from drying as described in [5], [6] and [7]. All panels were tested at 28 days after the construction.

2.2 Characteristic compressive strength of masonry

To determine of compressive strength of masonry, tests were carried out in accordance with [5]. Three specimens of nominal size 600 mm (length) x 600 mm (height) x 300 mm (thickness) have used and size was selected considering the specifications given in [5]. Specimens were built on flat horizontal surfaces and load was applied using a hydraulic jack with a proving ring to measure the load. A steel plate was kept on top of the specimen for the uniform application of the load throughout the top surface. (see Figure 1).

Fig 1: Load application of the compressive strength test

2.3 Characteristic flexural strength of masonry

Tests for determination of flexural strength of masonry have been carried out in accordance with [6]. Tests were carried out for both horizontal plane of bending and vertical plane of bending. Specimens were constructed on two layers of polythene sheets which were placed on timber planks to ensure that the base is free from frictional restraint. Immediately after the completion of construction of specimens, they were pre-compressed using concrete cubes with a vertical stress of 3.5×10^{-2} N/mm^2. Specimens have tested after 28 days under four-point loading and load was applied to the specimens through inner bearings while two outer bearings were used as lateral supports. Three specimens were tested for each plane of bending and three additional set of readings were obtained from the previous study [8] in order to calculate characteristic flexural strength and to take account for the variations in the workmanship.

2.3.1 Testing for flexural strength of RRM when plane of bending is horizontal

Specimens of 1400 mm (length) x 1000 mm (height) x 300 mm (thickness) in size were used for the test. Distance between inner supports is 450 mm and distance between outer supports is 1200 mm. (see Figure 2).

Fig 2: Test set up for flexural strength of RRM when plane of bending is horizontal

2.3.2 Testing for flexural strength of RRM when plane of bending is vertical

Specimens of 600 mm (length) x 1400 mm (height) x 300 mm (thickness) in size were used. Distance between inner supports is 450 mm and distance between outer supports is 1200 mm. The test set up is shown in Figure 3.

Fig 3 Test set up for flexural strength of RRM when plane of bending is vertical

2.4 Characteristic shear strength of masonry

[7] Specifies triplet test to determine shear strength of masonry. Triplet test procedure will provide two straight and parallel failure planes. In RRM, due to the random bond patterns, this type of straight failures cannot be expected and hence a different set up was developed and used in the investigation.

Three panels of 450 mm (length) x 600 mm (height) x 300 mm (thickness) in size were constructed and immediately after completion of construction of specimens, they were pre-compressed using concrete cubes with a vertical stress of 3.5×10^{-3} N/mm^2. In this study, all three specimens were tested with zero pre-compression (axial load) and additional three readings from a previous study [8] were used to calculate characteristic shear strength. Figure 4 shows the test set up used for this test.

Fig 4: Test set up for shear strength of RRM

2.5 Characteristic compressive strength of masonry units (stones)

Compressive strength of stones were determined in accordance with [9]. Six cubes of approximately 50 mm in length were cut from stones and polished the surfaces as recommended in [9].

Three specimens were tested in saturated condition by immersing them in water and maintained at 20^{o}C to 30^{o}C for 72 hours before testing. Other three specimens were tested in dry condition by oven drying at 105^{o}C for 24 hours before testing.

3. Experimental results

3.1 Compressive strength of masonry

The compressive strength results obtained for each RRM wall panel are given in Table 1. In accordance with [5], characteristic compressive strength of RRM is 1.1 N/mm^2.

Table 1: Compressive strength of RRM

Panel No.	Failure load (kN)	Plan area (x10^3 mm^2)	Compressive strength (N/mm^2)
1	268.8	180.6	1.49
2	236.8	184	1.29
3	212	179.7	1.18

3.2 Flexural strength of masonry

Flexural strength of each specimen was calculated according to the equation given in [6].

$$f_{xi} = 3F_{i,\,max}(l_1 - l_2) \;/\; 2bt_u^2 \qquad (1)$$

Where,

$F_{i,max}$ - Maximum load, l_1 -spacing of outer supports = 1200 mm, l_2 – spacing of inner supports = 450 mm, b – width of masonry in plane of bending and t_u – width of masonry units.

Width of masonry units was taken as 300 mm (width of section in plane of bending) which will give a conservative result.

The test results and calculated characteristic strengths of RRM are given in Table 2 and 3.

Table 2: Flexural strength of RRM when plane of bending is horizontal

Specimen No.	Failure load (kN)	Width of section in plane of bending (mm)	Flexural strength (N/mm^2)
1	27.18	1000	0.34
2	26.48	1000	0.33
3	21.73	1000	0.27
4*	37.28	1000	0.47
5*	39.87	1000	0.50

(* Test results from previous test series by [8])

Characteristic flexural strength = 0.25 N/mm^2

Table 3: Flexural strength of RRM when plane of bending is vertical

Specimen No.	Failure load (kN)	Width of section in plane of bending (mm)	Flexural strength (N/mm^2)
1	18.38	600	0.38
2	12.00	600	0.25
3	19.97	600	0.42
4*	5.18	560	0.12
5*	5.18	565	0.11
6 *	5.18	560	0.12

(* Test results from previous test series by [8])

Characteristic flexural strength = 0.05 N/mm^2

3.3 Characteristic Shear Strength

Table 4: Shear strength test results

Specimen No.	Failure load (kN)	Area ($x10^3$ mm^2)	Shear strength (N/mm^2)
1	6.545	162.8	0.040
2	6.775	137.3	0.049
3	5.113	137.4	0.037
4*	5.273	138.8	0.038
5*	8.954	139.9	0.064
6*	3.374	140.6	0.024

(* Test results from previous test series by [8])

Characteristic shear strength = 0.02 N/mm^2

3.3 Compressive strength of stones

Table 5: Compressive strength test of stones

Condition	Specimen No.	Failure load (kN)	Area (mm^2)	Compressive strength (N/mm^2)
Saturated condition	1	57.5	2703	21.27
	2	80.9	2970	27.24
	3	92.4	2704	34.17
Oven dry condition	4	56.6	2601	21.76
	5	64.3	2601	24.72
	6	53.4	1764	30.27

Average compressive strength of stones in saturated condition = 27.56 N/mm^2

Average compressive strength of stones in oven dry condition = 25.58 N/mm^2

Average compressive strength of stones = 26.57 N/mm^2

4. Analytical study

Following general properties of soil and RRM were considered for the analysis and assumed the water table is below the retaining wall base level.

Density of backfill = 17 kN/m^3, density of RRM = 22 kN/m^3, surcharge pressure = 10 kN/m^2, shear strength parameters of the backfill – C = 0, Φ = 30°. Angle of friction between the base and foundation soil δ = 30°. Allowable bearing capacity of the underneath soil = 250 kN/m². A 3000 mm of retaining soil height and 450 mm embedded in to the ground have been considered in analysis.

In the study, four failure criteria have been considered. See Table 6 for details.

Table 6: Failure criteria of retaining wall

Failure criteria	Factor of safety
Overturning	1.5
Sliding	1.5
Maximum bearing pressure	Less than 250 kN/m²
Minimum bearing pressure	Greater than 0

In conventional method of design, flexural capacity of the RRM is neglected in the design. In this study, the flexural strength of RRM obtained from experimental results was used to optimize the design. Generally flexural stresses develop at the heel of the wall and it was checked that flexural strength of masonry is higher than those stresses.

Variation of the cross-sectional shape was also considered in the analysis for the optimization. Rectangular shape, with 2 steps, 3 steps, 4 steps and 5 steps were the cases considered in the analysis. Figure 5 shows the different cross-sectional shapes considered. Equal rise and goings have been considered for convenience of analysis. In all cases, the critical criterion to decide base width was the minimum base pressure according to the analysis. Table 7 shows the results obtained from the analysis considering conventional and optimized methods for different cross-sectional shapes.

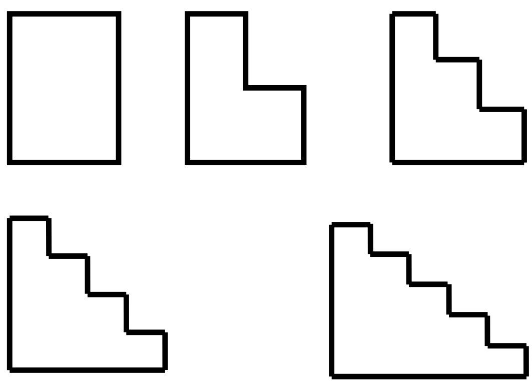

Fig 5: Cross-sectional shapes of RRM walls considered

Table 7: Details of retaining wall design

Retaining wall type	Conventional method		Optimized design	
	Base width (m)	Cross sectional area (m²)	Base width (m)	Cross sectional area (m²)
Rectangular	2.2	7.59	1.7	5.865
2 Steps	2.4	6.216	1.8	4.662
3 Steps	2.4	5.52	1.8	4.14
4 Steps	2.4	5.184	1.8	3.888
5 Steps	2.4	4.968	1.8	3.726

Figure 6 shows the variation of cross-sectional area with the increase of number of steps for conventional design method and optimized method considering the flexural capacity of RRM. Costs are calculated in accordance with the [10].

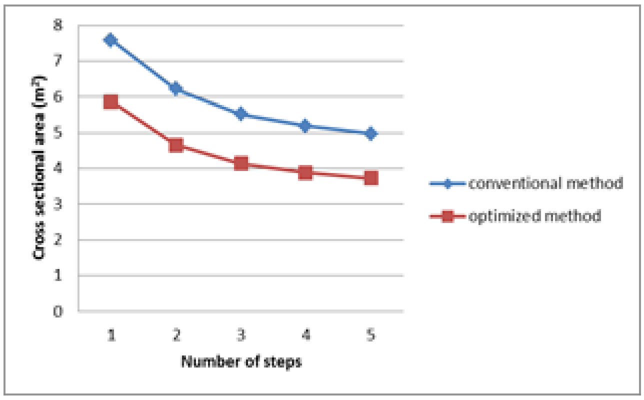

Fig 6: Comparison of analytical results

Table 8: Cost comparison of retaining wall designs

Retaining wall type	Cost per meter length (Rs.)		Cost reduction per meter length (Rs)	Cost reduction %
	Conventional method	Optimized design		

Rectangular	75095	58028	17067	22.7 %
2 Steps	61501	46126	15375	25%
3 Steps	54615	40961	13654	25%
4 Steps	51290	38468	12822	25%
5 Steps	49153	36865	12288	25%

5. Conclusions

From the experimental study, following characteristic strengths of RRM were found. These characteristic strength values are for 1:5 mortar designation and masonry units having an average compressive strength of 26.5 N/mm². Workmanship also has a greater impact on the characteristic strengths of RRM.

Characteristic compressive strength = 1.1 N/mm²

Characteristic Flexural strength

When plane of bending is horizontal = 0.25 N/mm²

When plane of bending is vertical

= 0.05 N/mm²

Characteristic shear strength = 0.02 N/mm²

According to the analytical results, it can be concluded that RRM retaining wall design can be optimized by using characteristic flexural strengths and considering step type cross section to achieve cost effective design. When number of steps increases, rate of cost reduction decreases. Increase in the number of steps does not have much effect when there are more than 3 steps. Adopting higher number of steps can lead to difficulties in construction and consume more time. Hence number of steps should be decided considering both design and construction aspects.

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