



ORIGINAL ARTICLE

The stability of gabion walls for earth retaining structures

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Abstract The stability of earth retaining structures in flood prone areas has become a serious problem in many countries. The two most basic causes of failure arising from flooding are scouring and erosion of the foundation of the superstructure. Hence, a number of structures like bridges employ scour-arresting devices, e.g., gabions to acting on the piers and abutments during flooding. Research was therefore undertaken to improve gabion resistance against lateral movement by means of an interlocking configuration instead of the conventional stack-and-pair system. This involved simulating lateral thrusts against two dimensionally identical retaining wall systems configured according to the rectangular and hexagonal gabion type. The evolution of deformation observed suggested that the interlocking design exhibits better structural integrity than the conventional box gabion-based wall in resisting lateral movement and therefore warrants consideration for use as an appropriate scour-arresting device for earth retaining structures.

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1. Introduction

According to the US Federal Highway Administration, up to 60% of bridge failures were caused by natural phenomena, especially from flooding [1]. It is apparent that since the past two decades, this ratio has not appreciably changed in many countries.

The two leading causes of failures from flooding are scouring (which can also occur without flooding) and debris impact against bridge superstructure. This debris can also reroute flows, resulting in aggravated scouring and/or increased horizontal pressures acting on bridge piers and abutments.

As known, scouring is the result of the erosive action of running water, which excavates and transports material away from the banks of streams and waterways. Different types of material scour at different rates and conditions, i.e., loose granular soils would scour more rapidly compared to cohesive soils. In addition, shifting of the stream may aggravate scour by eroding the approach roadway or changing the waterway's flow angle. Lateral movement of a waterway is affected by stream geomorphology, diversions, and characteristics of its bed and bank materials. For this purpose, gabions have long been used as scour-arresting devices on bridge abutments and piers. Apart from fortification against flooding, gabion walls are also suited to the following cases:

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1. Poor orientation of bridge piers with respect to water flows.
2. Large restrictions in flow imposed by the bridge superstructure.
3. Fine-grained materials, susceptible to move with a small increase in flow velocity.
4. Unpredictable increases in the water flow, e.g., during monsoons.

1.1. Gabion wall failures in hostile environments

Despite many apparent advantages of gabion walls in protecting bridges against aggravated scour, failures can occur if the walls are subjected to high magnitudes of lateral forces. The sudden increase in lateral thrusts tends to cause side-shifting of adjacent gabion units configured in a conventional stack-and-pair arrangement. The end result is usually large-scale lateral movement of the affected abutment or pier.

Conventional bridge designs often initially incorporate drainage mechanisms behind the backwalls and wingwalls of their abutments. The mechanism is usually achieved by depositing free-draining backfill material behind the wall, collecting the seeped-through water and discharging it into an inlet connected to a storm water system. However, clogging of the drainage system can result in accumulated hydrostatic pressure behind the wall over time, subjecting the pier and/or abutment to overstressing, consequently leading to unacceptable lateral movement. (The damage is usually more severe in cold countries, owing to repeated freezing and thawing of the accumulated water.)

When gabions are used to fortify bridge abutments and piers, the integrity of structural fixity remains the core factor in preserving bridge stability in such hostile environments. In a conventional stack-and-pair configuration of gabion units, resistance to the lateral shifting on individual units rests almost exclusively to the tie wires connecting adjacent units. There is virtually no contribution of the remaining structural components constituting the gabion unit in resisting these aggravated lateral forces, e.g., the frame, mesh, or stone fill. Since gabions are essentially gravity structures, which rely on their weight to achieve stability against lateral forces, any increase in gravity function would entail increasing their individual masses. This solution may not only be inefficient from a material perspective, but also pose settlement problems.

To resolve this problem, a research was undertaken to examine the feasibility of using an interlocking configuration of gabion units, instead of the traditional stacked-and-paired system. The system employs a continuum of hexagonal gabions to interlock with one another by virtue of shape and configuration. The new gabion design is functionally similar to the conventional box gabion, but modified conceptually in accordance with the York method used in concrete wall facings [2].

1.2. The interlocking gabion design

A simple observation of naturally occurring structures (e.g. bees' nets or crystalline arrangement for metals) suggests that in any structural continuum, interlocking properties and individual unit shape determine overall structural performance. An extrapolation of this hypothetical principal in cellular-based retaining structures, e.g., gabion walls suggest the following two possibilities:

1. A hexagonal-shaped gabion displays better strength capabilities as opposed to the conventional rectangular-shaped gabion.
2. A retaining wall composed of an interlocking system of individual gabion units display better overall structural integrity compared to a system of conventional stacked-and-paired gabions units.

These questions effectively reflect the principle that form influences function. To this end, the results of individual and cumulative experimentation investigating the hexagonal gabion's responses to external load vis-à-vis the traditional design would be examined. The findings intend to promote a new and useful contribution to the field of design and construction of such structures by disseminating the research results to the attention of engineers and offering alternate design solutions.

1.3. Technical and functional characteristics

Gabion walls are cellular structures, i.e., rectangular cages made of zinc-coated steel wire mesh and filled with stone of appropriate size and necessary mechanical characteristics. Individual units are stacked, paired, and tied to each other with zinc-coated wire (or fasteners) to form the continuum. The choice of the materials to be used is fundamental for obtaining a functionally effective structure. In particular, the mesh must satisfy the requirements of high mechanical and corrosive resistance, good deformability and lack of susceptibility to unravel. The conventional gabion possesses some peculiar technical and functional advantages as follows:

1. They are reinforced structures, capable of resisting most types of stress, particularly tension and shear. The mesh not only acts to contain the stone fill but also provides a comprehensive reinforcement throughout to structure.
2. They are deformable structures, which (contrary to popular opinion) does not diminish the structure but increases it by drawing into action all resisting elements as a complex reinforced structure, facilitating load redistribution.

They are permeable structures, capable of collecting and transporting groundwater and therefore, able to attenuate a principal cause of soil instability. The drainage function is further augmented by evaporation generated by the natural circulation on air through the voids in the fill.

They are permanent (and therefore durable) structures, with a virtually maintenance-free regime from effects no more severe than the natural aging of any other structure (with the exception of highly corrosive environments). Furthermore, their characteristics over time tend to gravitate toward establishing a natural state of equilibrium.

They are easily installed, i.e. that deployment is possible without the aid of special equipment of highly trained personnel. This aspect is notably important in river and marine reclamation, where rapid intervention to retain soil is often necessary and/or when post-deployment modifications are necessary.

2. Theory

Although retaining walls imply resistance to movement, some forms of horizontal and vertical wall yield are still anticipated.

This horizontal (i.e. sliding) and vertical movement (i.e. settlement) is essentially a manifestation of the resultant pressures acting behind the wall surface [3,4]. The resultant pressure, P , is always thought to act upon an inclined plane at a third of the wall's height from its toe [5,6]. Although its computed angle of inclination and height is specific computed figures, it is clear that determination is based on a series of assumptions, depending on which classical theory was subscribed to during analysis (i.e., Rankine vs. Coulomb). The fact that the total resultant pressure, P , acts along an inclined plane suggests that P may be derived into its horizontal and vertical components. Therefore, different walls would invariably withstand different magnitudes of each force component.

This argument sets the premise that the shape and orientation of distinct gabion designs (i.e., rectangular vs. hexagonal) will likewise result in distinct capabilities to absorb one (or both) of the force components constituting the resultant lateral pressure, P . As a basis for comparison, both types of gabions must conform to similar dimensions, so that shape and orientation remain the determining variables in evaluating various structural properties associated with each gabion type. The research therefore compares the rectangular gabion (also referred to as the box gabion) with the hexagonal gabion to investigate the mechanical responses of either type of structure to external load, both individually and in a cumulative setting.

3. Formulation of test specimens

As tests on full-scale mock-up units are impractical, samples were scaled down to approximately 40% of commercial gabions. A total of 129 gabion samples were prepared for constructing the twin simulation walls, comprising 50 hexagonal units. All samples were formulated by hand, utilizing two types of bars for the frame.

The first stage of sample formulation involves forming the requisite frames defining each gabion shape. These were fabricated from typical plain round, 6 mm mild steel bars, with a characteristic strength of 250 N m m^{-2} . The second stage involves covering the frame with BRC wire mesh, which was cut to size with a slight overlap for tension reinforcement. To minimize lateral movement, the mesh is tied to the R6 frame with zinc-coated steel wire of 1.60 mm thickness. The third stage involved the filling process, whereby selected crusher-run stones between 25 and 50 mm are filled by hand up to each gabion's full height. Once the gabions are filled, all samples are sealed and hosed to expel impurities and to expedite fill readjustment.

A typical design of each type of gabion unit is shown in Fig. 1. A schematic representation of the each type of gabion unit is shown in Fig. 2, while technical dimensions of 10% of the test specimens are presented in Table 1 for types A (hexagonal), B (rectangular), and C (semi-hexagonal). X , Y , and Z denote standard Cartesian planes, whereas void ratio is simply expressed as percentage disparity between aggregate rock density (2500 kg m^{-3}) and apparent gabion density.

4. Construction of twin walls

Two sets of retaining walls composed of each gabion type were constructed for evaluating the mechanical responses of the conventional gabion wall versus the hexagonal wall to external load. The walls were of 1.80 m height and 1.75 m width and

spaced 1.80 m from each other as shown in Fig. 3. The height-to-base ratio of each wall was purposely designed to be excessive in order to permit large deflections, although overturning moments were not tolerated in the interest of safety. Each wall was built with a stepped front-face and smooth back-face that reduces the wall thickness by 50% at three-fifths of the wall height from its base to the top.

The space between both walls was closed-off with plywood restraining panels to create a boxed area for the subsequent loading stage. The entire "box" was covered with plastic sheeting as an impervious membrane, purposely oversized to accommodate large moments expected of both structures.

A maximum soil-hydrostatic head of 1.80 m and average per unit gabion density of 2000 kg/m^3 will be assumed. The twin wall system employs reduced safety factor, i.e., 1.30 against overturning and 1.10 against sliding using a predetermined soil angle of internal friction, maximum bearing pressure and stone average shear stress.

5. Research issues

Several pertinent issues arise from evaluating the behavior of both walls under extreme loading:

1. The gabions' abilities to collectively deform under aggravated loads when combined soil-hydrostatic pressures are involved. Reversibility (or irreversibility) of deformation at low stress values was a point of contention.
2. The rate in which deformation occurs from changes in displacement under progressive loads. These conditions represent the successive increments in soil lateral thrust occurring at the back of a retaining wall from fluctuations in the backfill's water content.
3. The nature of the process of deformation in terms of localized mechanical responses when loaded over an indefinite period. Assuming that localized response is prevalent, it would be necessary to evaluate what factors resulted in the unstable equilibrium.
4. Evaluation of the structural characteristics of both walls at the point of terminal failure, i.e., when the structures have been loaded to maximum capacity. Of particular interest would be if the final load leads to abrupt collapse (or susceptibility to collapse)

6. Evaluation of deformation

The basis for comparing both walls is visual deformation, i.e., changes in horizontal and vertical displacements of an arbitrary point (on the walls' surfaces) vis-à-vis its original position (Fig. 1). The assumed plane of deformation is represented along the two-dimensional exterior cross-section of either wall. A standard cartesian system was adopted to measure the extent of displacement occurring on both walls under the same stress magnitudes.

The cartesian reference grid covers the cross-section of both walls with a matrix of 220 points, based on a specified number of horizontal and vertical gridlines superimposed on each wall. Shifting observed of each point was compared with a permanent vertical line to establish deformation under load. Each point was tagged and measured for horizontal distance from the fixed benchmark to establish relative initial position. For

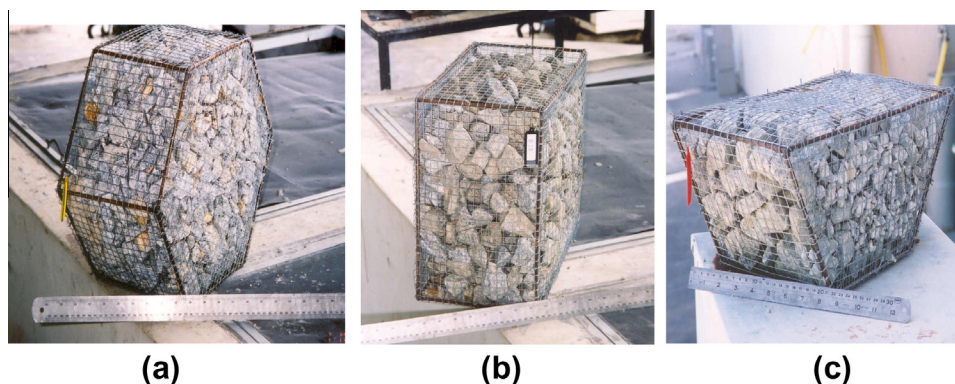


Figure 1 (a) Hexagonal, (b) rectangular, and (c) semi rectangular shape of gabions.

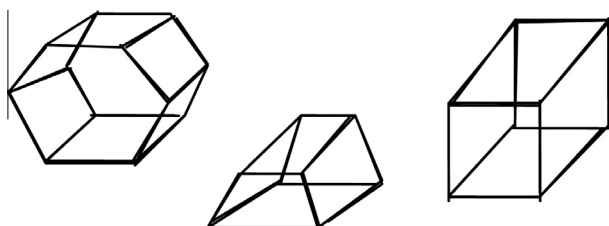


Figure 2 Hexagonal (left), semi-hexagonal (center) and rectangular gabion (right).

Table 1 Principal dimensions of gabion test samples.

Unit	H (cm) ^a	Mass (kg)	Volume (cm ³)	Density (kg/m ³)	V. ratio (%)
A01	19.9	40.3	21,590	1866.6	25.34
A02	20.0	39.6	21,326	1856.9	25.72
A03	19.5	37.6	20,979	1792.3	28.31
A04	20.5	41.2	21,982	1874.2	25.03
A05	20.2	40.9	22,151	1846.4	26.14
B01	19.8	40.9	24,186	1691.0	32.36
B02	20.6	42.4	26,619	1592.8	36.29
B03	20.5	40.9	27,141	1506.9	39.72
B04	20.4	41.5	26,145	1587.2	36.51
B05	21.6	42.8	27,904	1533.8	38.65
C01	20.6	20.1	10,721	1919.3	23.23
C02	20.5	20.2	10,828	1949.5	22.02
C03	21.0	20.6	10,511	1884.2	24.63

^a H refers to average specimen height.

easy identification, standard Roman alphabets were used to represent the horizontal grids and Arabic numerals for the vertical grids.

A digital theodolite was used to determine the horizontal displacements of all principal points as a function of their viewed angular shift. The instrument was used to ascertain all readings from two measuring stations, each placed directly opposite each wall type. The soil load was applied by manually filling the walls' expandable "tank" in successive increments. For obvious reasons, "unsuitable" material was selected to impose higher lateral thrusts against both walls. The imposition of incremental soil load permits progressive assessments pertaining to the mechanical responses of each structure at that particular load level.

The walls were loaded to 0.075H, corresponding to a load of approximately 1250 kg for the purpose of establishing initial wall inertia and mobilize active thrust. Following that, the walls were loaded to 0.375H (6250 kg), 0.5625H (9375 kg), and 0.75H (12,500 kg). Finally, hydrostatic pressure was applied gradually up to full wall height, i.e., 0.75H soil + 0.25H hydrostatic head.

6.1. Test results

Tacheometric measurements of all moving targets under progressively increasing load enabled conversion into horizontal and vertical displacement with respect to the fixed vertical line. From the data generated, it is possible to determine the average values for deformation at various wall heights for each loading stage. On plotting these results, the evolution of the average deflection along the wall as a function of the soil-hydrostatic load is illustrated.

The evolution of deformation observed on both test structures necessitates empirical assessment. For this purpose, a series of profile-graphs depict the shift in horizontal positions for each moving target on the reference grid for load conditions 0.075H, 0.1875H, 0.375H, 0.5625H, 0.75H, and the final 0.75H + 0.25H hydrostatic head stage. The evolution of vertical displacements was purposely omitted as they were found to be both erratic and insignificant (i.e., with average relative displacements of only 0.001%). This was observed for all vertical gridlines 1, 2, 3, 7, and 9 for the rectangular wall and 4, 5, 6, 8, and 10 for the hexagonal wall.

The observations present several interesting findings. The actual linear shifts established along the cartesian X plane and the percentage change in each corresponding shift relative to its preceding position describe the stability of both walls. For practical purposes, six stages of wall deformation were deemed sufficient for interpretation. Since load conditions were identical, the limits were simply indicated in terms of the height of the soil mass as a function of the total wall height. Movement was designated in terms of X_0 , X_1 , X_2 , X_3 , X_4 , and X_5 , each corresponding to a soil height of 0.075H, 0.1875H, 0.375H, 0.5625H, 0.75H, and 0.75H + 0.25H hydrostatic head.

Issues pertaining to the structural integrity of each test wall system will be assessed upon evaluating the visual deformation of each principal grid line, i.e., lines 1, 2, and 3 (for the rectangular wall configuration) and 4, 5, and 6 for its hexagonal



Figure 3 Different types of wall gabions constructed for the test model.

counterpart. Figs. 3 and 4 show lateral displacements versus wall height for all loading stages. Upon plotting the results, the scatter was found to be relatively minor, and after discarding anomalies, the average values obtained for deflection were deemed dependable. This therefore permits a largely accurate illustration of the evolution of observed deflection as a function of load, presented as follows in Figs. 3 and 4.

7. Discussion of results

The results indicate that the hexagonal gabion exhibits better overall structural integrity than the conventional gabion in terms of deformation resistance and susceptibility to collapse. The shear behavior exhibited by each wall illustrates the principal link between unit configuration and overall stability when cellular units are built into a continuum. These assertions undoubtedly present major implications when considering practical application in bridge design, where such mechanical advantages, when magnified, may mean the difference between success or failure in the performance of piers and/or abutments fortified with cellular-based retaining structures against scour.

The lines depicting the evolution of each principal vertical grid on the external cross-sectional faces of the test walls depict actual wall profiles for each loading stage. Foremost, it is possible to assert that the two sets of principal vertical gridlines are largely consistent in terms of their average deflections at the various loading stages. All line movements for the first three loading stages (i.e. 0.075H, 0.1875H, and 0.375H) essentially register common gradients, whereas line movements for the last three stages (i.e. 0.5625H, 0.75H, and the terminal

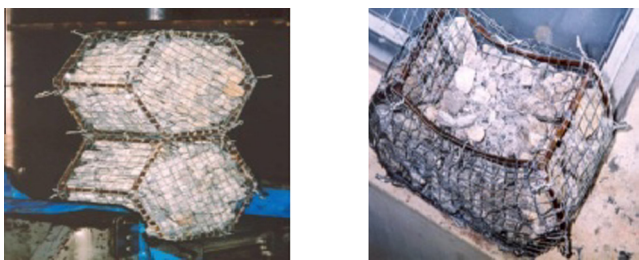


Figure 4 Load application on the gabion units and their mode of failure.

state) correspond to a reduced gradient. Trend lines established for each curve suggest a polynomial expression for lateral displacement versus load, and that the rate of displacement change for the last three load stages is significantly higher than the initial three.

A possible explanation is that during the initial loading stages, the resultant earth pressure is used to increase structural inertia. Initial sliding on the hexagonal wall experienced is much lower, i.e., only 7.6% for the first three load stages (compared to its maximum deflection) and 10.8% for the last three loading stages. The maximum deflection observed on both walls clearly indicates that the hexagonal-configured wall deforms less and under more controlled outcomes than the rectangular wall. In terms of the vertical lines' shifts for the last three load stages, the grid points on the rectangular wall deflect some 1000%, 350%, and 73%, compared to the same moving targets positioned on the hexagonal wall, which deflect about 180%, 17%, and 35%, respectively.

This observed erratic behavior of the rectangular-configured gabion wall has tremendous implications in its inherent resistance to deformation, which consequently reflects upon its stability when responding to increasing lateral thrust. This is evident from its profile itself at the region between 0.35H and 0.55H, where the zigzagging pattern clearly indicates shear failure.

Despite the polynomial relationship of wall movement versus load from initial to full load, a more linear relationship is evident if movements are strictly assessed above the walls' critical 0.33H height, where the resultant earth pressures are believed to act. In the case of both walls, the average gradient values obtained for the first three load stages were -0.135 , -0.113 , and -0.114 for lines 1, 2, and 3, respectively. The last three load stages, however, produced a marked shift in gradient, i.e., 0.052, 0.050, and 0.051 for the same gridlines. This radical change in gradient sign convention demonstrates the high shear stresses imposed on the rectangular wall at the "shear zone" of 0.35H – 0.55H. The hexagonal wall, on the other hand, registers milder curve gradients of -0.198 , -0.248 , and -0.263 for lines 4, 5, and 6 (for the first three load stages) and subsequently -0.051 for all Lines for the last three load stages. A consistent sign convention indicates lower shear levels and hence lower susceptibility to shear failure at the same zone.

8. Conclusions

The technical focus of this research invariably arises from a social perspective, namely is addressing the alarming trend of scour-induced bridge failures through innovation and improvisation of a common abutment/pier protection device—the gabion wall. By examining the century old pair-and-stack method of using "rock cages" to retain earth vis-à-vis an interlocking alternative comprising a hexagonal design with interlocking properties, the link between shape and structural function has been addressed.

The study outcome and subsequent interpretation of findings suggest several pertinent conclusions as follows:

1. Comparison of average deflections between both walls suggests that the hexagonal-configured wall deforms under more controlled outcomes compared to its rectangular counterpart. This invariably suggests that lateral deformation exhibited by an interlocked gabion system is more

stable than a conventional stacked-and-paired system. This observation undoubtedly presents major implications in the continued utility of conventional gabions with respect to deformation resistance under gradually increasing lateral thrust.

2. An examination of wall profiles at the region between $0.35H$ and $0.55H$ clearly reveals severe shear-induced deformation of the rectangular wall compared to the hexagonal wall. This observation suggests that the hexagonal wall's inherent interlocking mechanisms operating at aggravated loads compensates for the observed excessive strains occurring at the 'shear zone'.
3. The deformation induced by the various loading stages is irreversible for both wall systems, which suggests that gabions, regardless of shape or configuration, do not behave as elastic structures.

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