# A STUDY OF BAMBOO REINFORCED EARTH RETAINING STRUCTURES

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**ABSTRACT**

Reinforced earth retaining systems became popular and came into extensive usage over the last two decades due to many advantages inherited in them. Different forms of reinforced earth systems had been developed in various parts of the world. For developing countries further advantages could be gained by incorporating locally available material.

In the Sri Lankan road network, reinforced earth retaining structures made of a tyre facing and bamboo reinforcement meshes were used at several locations. The cost of these structure were as low as 30 % of an alternate gravity form. These structures have performed satisfactorily for over ten years and the research reported in this paper was carried out to study their behaviour and to develop efficient design procedures. Pull out resistance of Bamboo meshes were determined and the tensile strengths were measured. A design method was developed based on these results.

Models done in the laboratory were subjected to different types of loading simulating the loading conditions in the field. Test procedures were designed to check the durability aspect of bamboos and to establish appropriate methods of preservation.

## PREAMBLE

In a reinforced earth retaining structure, the closely spaced reinforcements and the soil behave as one structural unit. One important aspect of a reinforced earth structure is its incremental form of construction. As the soil mass is partitioned, each portion receives support from a locally inserted reinforcing element. Thus it can be classified as an internally stabilized earth retaining structure. (Jones et al 1985). Reinforced earth retaining structures have many advantages due to their flexible nature, ability to tolerate large differential settlements and the speed of construction. For a developing country further advantages could be gained by incorporating locally available material.

## DESIGN PRINCIPLES OF REINFORCED EARTH STRUCTURES

A reinforced earth retaining structure should be designed to be stable both internally and externally. Externally, the reinforced block of soil is assumed to behave as a gravity structure. It should be capable of resisting overturning and sliding caused by the earth pressure acting at its back. The reinforced earth structure (block) can be separated into two zones as the active zone and the resistant zone as presented in the Figure 1. Soil in the active zone attempts to move outward and apply a frictional drag force on the reinforcing elements. Beyond that is the resistant zone and the pullout resistance of the reinforcing elements is developed due to the soil reinforcement interface friction and bearing resistance in the resistant zone.

For the structure to be internally stable the reinforcing elements should be capable of withstanding the tensile forces transferred to it through the frictional drag force, without leading to any tensile failure. They should also be embedded to a sufficient distance in the resistant zone to develop the necessary pullout resistance. As such, the two internally stability criteria are; the stability against tensile failure and the stability against pullout resistance.

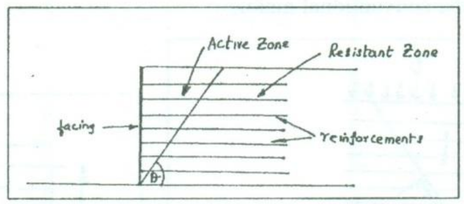



**Figure 1 – Active and Resistant Zones in Reinforced Earth**

The facing elements of a reinforced earth system can take a variety of forms. They may be formed from metals, precast concrete, brick work, gabions or geotextiles. The tensile forces in the reinforcements are small at the facing and thus the facings are not subjected to large loads. As such, they can be relatively light. Their primary function is to stop erosion of the fill and to ensure continuity, while providing a suitable architectural finish.

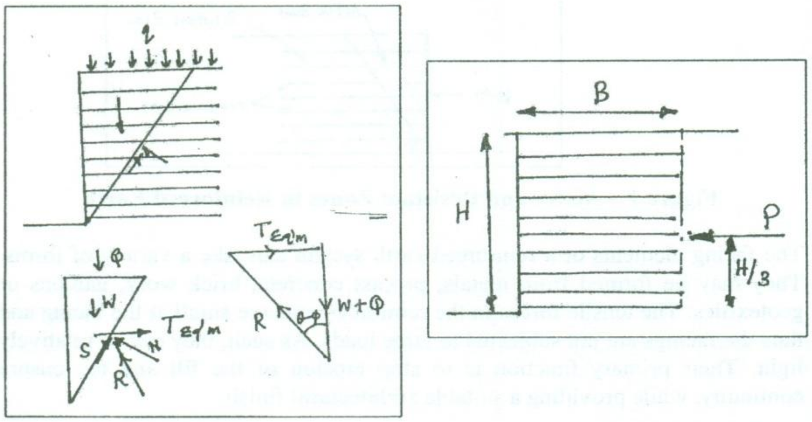
With strip type reinforcements resistance is developed solely from the interface friction. Pull out resistance is related to the friction angle of the soil and will depend on the roughness of the strip. In addition to the interface frictional resistance developed between the longitudinal reinforcements and the fill, the passive resistance developing in front of the transverse members will be effective in grid and mesh type of reinforcements. Research studies have revealed that the contribution from the transverse members is much more significant. With the introduction of these forms of reinforcements, the required frictional qualities of the fill could be relaxed to some extent.

**Stability Considerations**

Internal stability of a reinforced earth structure can be evaluated through a tie back wedge analysis done at different levels of the structure. At any given level of the structure the potential failure surface can be considered to be of the shape of a wedge (Figure 2 (a) ). A trial wedge considered will be in equilibrium under the forces W, T , S and $T_{eqm}$. The force $T_{eqm}$ is provided by the reinforcements intercepted by the wedge through their pullout resistance and tensile strength. An equilibrium analysis will enable the computation of the maximum value of $T_{eqm}$ for a given level. The capacity of the reinforcements $T_{sum}$ is the lower value of the summation of pullout resistances of the reinforcements and the summation of their tensile strengths.

The factor of safety on internal stability can be expressed as FOS = $T_{sum} / T_{eqm}$. If the summation of the pullout resistances is less than $T_{eqm}$, the structure will fail by pullout of the reinforcements. If the summation of the tensile strengths is less than the $T_{eqm}$ the structure will fail due to the tensile failure of reinforcements.

External stability is evaluated by considering that the reinforced block will behave as a gravity wall (Figure 2(b)). Factor of safety expressions can be derived against failure by overturning, sliding or for the bearing capacity failure in the conventional manner.




**(a) Internal Stability** **(b) External Stability**

**Figure 2 - Stability Criteria for Reinforced Earth Structures**

## BAMBOO REINFORCED EARTH RETAINING STRUCTURES IN THE FIELD

A number of earth retaining structures were constructed at several locations in the highway network of Sri Lanka with Bamboo reinforcements and discarded motor vehicle tyres as facing . In most instances these structures were used to rehabilitate failed slopes and for the widening of existing roads. In these structures, a Bamboo mesh prepared by placing strips in a 0.3 x 0.3 m grid were used. Tyres used as facing elements were connected to the Bamboo strips at the bottom using nylon strings of 6mm diameter. Clayey gravely lateritic fill material was placed on the Bamboo mesh and compacted to a height of about 0.3m. The tube space inside the tyres were filled with the same fill and well compacted. Another Bamboo mesh was placed on the compacted soil and connected to the next set of tyres placed on the top of the earlier set. This procedure was repeated to form a reinforced earth retaining structure of the required height. These bamboo strips were treated by immersing for one day in a copper sulfate solution of 3% by weight of water to improve the durability (Kulathilaka 2000(a)).

These constructions were done on personal judgment without any detailed design computations but the structures have performed satisfactorily for over

10 years. Hence there is a need to conduct studies to understand their behaviour and to develop rational design methods. There are historical records of the use of Bamboo reinforcements also. Madhav (1999) reported the case of an ancient. Buddhist monastery in India that had used this technique.

## BASIS FOR THE MODEL STUDIES

A study on the behaviour of a reinforced earth retaining systems would require loading of the structure and measurement of deformations and internal strains (and therefore stresses) in the reinforcements. It will also be necessary to load the structure until failure to identify possible failure mechanisms. Preliminary computations indicated that massive loads would be required to induce collapse of a real size structure. Also, the difficulties in attaching strain gauges to Bamboos and likely experimental errors were recognized. Hence it was decided to carry out the study through model tests.

The study was done through testing of model structures that were constructed inside a self contained loading setup in the laboratory. Bamboo reinforced walls were constructed incrementally from bottom up, following the field construction procedures as closely as possible. Due to the practical difficulties in using the bamboo mesh with small size model tyres, an Aluminium foil material was used to make the facing. Two types of fill materials; a sandy fill and a lateritic fill were used in the construction. The effect of saturation of the lateritic fill was also studied. Two types of loading conditions; a vertical load within the reinforced zone and a vertical load behind the said zone, were applied simulating the different types of loads a prototype structures could be subjected in its life.

Pullout resistance is one of the major factors deciding the internal stability of reinforced earth retaining structures. Studies were also done to determine the pullout resistance of Bamboos in both sandy soil and in lateritic fill. The long term behaviour of Bamboo reinforcements is a major questionable aspect. Therefore a test program was designed to study the deterioration and loss of strength of Bamboos when they are buried for a long time. The effectiveness of various preservatives such as Copper Sulphate, Potassium Dichromate and coal tar was also studied.

## EVALUATION OF PULL OUT RESISTANCE

The pullout testing was done with both sandy soils and lateritic fill. Bamboos were arranged in a 50 mm x 50 mm mesh. As the initial tests indicated the pullout resistance to be very high a mesh with only two longitudinal bars was used. Bamboo meshes were buried in a fill compacted inside a Perspex box. The box was stiffened by slotted angle sections and had Perspex on three sides and a slotted timber facing in front. Cables that were connected to the meshes separately, were taken out through the opening of the timber facing and connected to the loading hanger. The front cross bar of the mesh which was outside the fill was made of mild steel and the connection was done there. The loading arrangement is depicted in Figure 3.

In the series of tests done with a sandy material ten percent water by weight was added to form a good workable material. This water content was arrived at by a trial and error process. Sand was compacted at that moisture content to a controlled density of 1743 kg/m$^3$ by taking a steel roller over the sand layer placed. The shear strength parameters of the sand were determined through direct shear tests and values of c=0 and $\phi$ = 34 deg. were obtained.

The next series of pullout tests were conducted using a lateritic fill material commonly used in filling operations in the country. The particles greater than 5 mm in size were removed from the original soil. The fines had a liquid limit of 58.0% and a plastic limit of 42.6%. The specific gravity of the particles were 2.60. The optimum moisture content was found to be 25.0 % under standard Proctor conditions and the maximum dry density was 1650 kg/m$^3$ . Lateritic fill material that was placed at its optimum moisture content in layers was compacted with a specially made drop hammer of weight 6.0 kg and fall 0.550 m providing a compaction effort equivalent to that in the standard Proctor compaction test. The compacted fill was found to have shear strength parameters of c = 30.4 kN/m$^2$ and $\phi$ = 28.1 deg when tested in the standard direct shear test setup at a strain rate of 0.29 mm/min. The somewhat high cohesion value obtained could be mainly due to the matrix suction of the unsaturated compacted fill.

A desired loading intensity was applied on the top surface of the fill by jacking up against the loading frame. An increasing pull out load was applied by adding weight to the loading hanger gradually until the mesh was pulled out. The outward movement of the mesh with relative to a reference frame was measured with each load increment.

**Pullout Resistance of Bamboo Meshes in Sand**

Initially, the pullout was done under a vertical loading intensity of 25 kN/m$^2$. As the pullout load was increased the front cross bars of the mesh came out when applied loads were in the range of 80 -100 kg and the mesh could not be pulled out. Next series of pullout tests were done under the self weight of the fill only without the application of any additional vertical surcharge. In this test, the two bamboo mesh reinforcement were pulled out completely at the applied loads of 16 and 60 kg respectively. The vertical stress due to overburden at the levels of mesh reinforcements were 0.48 kN/m$^2$ and 1.54 kN/m$^2$ .

<u>Estimation of a Bond Coefficient $f_b$</u>

For mesh or grid type reinforcements pullout resistance is a combination of interface frictional resistance and the passive resistance in front of the transverse bars. Although an expression can be derived considering the above effects, the usual practice adopted with the mesh and grid reinforcements is to express the pullout resistance in a simplified form with the help of a bond coefficient $f_b$. The bond coefficient $f_b$ is given by the relationship;

$$T_P = f_b \times \sigma_V \times \tan\phi \times B \times L \times 2$$

Using the applied pull load just prior to the failure of the front cross bar, in the test done with a surcharge, $f_b$ coefficients of 0.84 and 0.98 could be obtained. It should be noted that this does not correspond to a pullout failure. In the test carried out with only self weight $f_b$ coefficient corresponding to pullout failure is 3.54 and this is much higher that values reported in literature.

**Pullout Resistance of Bamboo Meshes in Lateritic Fill**

Similar pullout tests were conducted with a lateritic fill material. With the application of the pullout loading under an applied surcharge of 10 $kN/m^2$ at a pullout load of 110 kg, the front bar of the mesh came out. Thus the pullout capacity should be greater.

Estimation of a Bond Coefficient

Considering the high apparent cohesion that exists in the unsaturated compacted fill it is more appropriate to use the definition as;

$$T_P = f_b \times (c + \sigma_V \times \tan\phi) \times B \times L \times 2$$

Using this definition the bond coefficient was found to be greater than 0.925.

**MODEL STUDIES ON BAMBOO REINFORCED EARTH RETAINING STRUCTURES**

Two types of loading was applied on the constructed wall. They are:
(a) a vertical load within the anchor zone and
(b) a vertical load behind the anchor zone.

A reinforced earth structure forming a highway abutment where the main load is applied vertically on top is simulated by the application of a vertical load within the reinforced zone (Figure 4 (a)). A structure constructed at the foot of a slope to provide stability can be simulated by applying a vertical load behind the anchor zone ( Figure 4(b)).

Model bamboo reinforced structures were constructed using a 50 mm X 50 mm grid. Meshes were placed at a vertical spacing of 75 mm. An Aluminum foil used in ventilation work was taken as the facing material. At each layer Aluminum foil was folded back by 50 mm and tied to the Bamboo reinforcements.

Model studies were done with both the sandy fill and the lateritic fill. The preparation of soil and the placement and compaction in layers during the incremental construction was also carried out in the same manner as in the case of pullout tests. The construction stages of a Bamboo reinforced model wall is presented in Figure 5. Loading arrangement for loading within the reinforced zone and the arrangement for the measurement of outward movement of the wall is depicted in Figure 6. In order to make sure that load is transferred uniformly, two jacks were positioned at equal distances and several timber planks were placed under the jacks.

**Results of the Model Studies With a Sandy Fill**

Loading within the reinforced zone

A model of height 500mm, length 1150 mm and cross sectional width 400 mm was constructed inside the Perspex box. To simulate the condition of a compressible founding soil 200 mm thick sand layer was placed at the bottom of the Perspex box. The model wall consisted of six Bamboo mesh reinforcement layers spaced at 75 mm vertical intervals and this thickness was done in two layers. The alternate layers were coloured with a black dye to facilitate the observation of deformation patterns and cracks at the onset of failure. Displacements of the wall facing were measured at three vertical sections at load increments of 20 kN/m$^2$. The vertical surcharge could be increased to an intensity of 260 kN/m$^2$. The outward movement of the wall facing with the incremental loading is presented in Figure 7 (a) without any indication of failure. The excessive surface settlements at this stage cause the loading system to slip and test had to be terminated.

Load Applied Behind The Reinforced Zone

Preparation of the model was similar to that in the previous test. The outward displacement of the wall facing was measured at load increments of 5 kN/m$^2$. The deformation pattern of the facing at each load increment is shown in Figure 7 (b). When the vertical surcharge was 45 kN/m$^2$ , a horizontal crack appeared on the surface at the edge of the loading plate. A thin vertical crack was also observed through both sides of the Perspex box at the end of reinforcement meshes. When the load was further increased the vertical cracks continued to move downwards to bottom level of the wall as shown in Figure 8. At the bottom of the wall these cracks changed in direction and continued in a horizontal direction towards the facing.

With the increase of the vertical surcharge the width of the cracks gradually increased and when the surcharge reached 90 kN/m$^2$ further increase of load was not possible as the displacements were increasing at a rapid rate. Thus the wall was deemed to have failed at the load intensity of 90 kN/m$^2$. It should be noted that, had the wall behaved like a gravity wall of height 300 mm and width 400 mm, it should have failed by sliding at a surcharge of 29 kN/m$^2$ and failed by overturning at a surcharge of 47 kN/m$^2$.
It is evident from these observations that when load is increased the reinforced area tends to separate from rest of the soil fill. This complies with the basic

theory of reinforced earth structures that the reinforced area acts as a single structural gravity wall unit. However, it was also clearly shown that the load causing this outward movement is much greater than the theoretical load causing external instability by either overturning or sliding. Thus, with a reinforced earth type structure, the safety margin against external stability is greater than in the case of a conventional gravity structure of similar weight.

**Results of the Model studies with a lateritic fill**

The next series of model tests were done with a lateritic fill. The soil preparation and compaction procedures were same as that adopted for the pull out tests. The two different types of loading were applied. In addition a loading under saturated conditions was also carried out.

Loading of the model within the reinforcement zone

The wall could be loaded to an intensity of 300kN/$m^2$. The outward movement of the wall facings were less than for sand model and were within 4 mm. The loading had to be terminated at this stage due to excessive bulging of the Perspex box.

Loading of the model behind the reinforced zone

The wall could be loaded to an intensity of 280 kN/$m^2$ before the loading system slipped. The observed outward wall movements were less than 3 mm and there were no signs of a catastrophic failure or outward movement of the wall as in the case of walls made with the sandy fill

**Testing of the Models with Lateritic Fill Under Saturated Conditions**

As the lateritic fill materials are not free draining it was appropriate to simulate the conditions of the structure subjected to a heavy prolonged rainfall. This was done by sprinkling water over the structure for a period of 1 week. As before, two types of loading conditions were adopted.

Loading of the saturated model within the reinforced zone

The wall could be loaded to an intensity of 160 kN/$m^2$ on top of the reinforcements and the outward movements of around 8 mm seen at this stage were greater than corresponding movements for the unsaturated model. It could be seen that the Aluminum facing has experienced an extension under the applied loading and a block of soil enclosed within the facing is seen to have separated from the rest. A crack could be seen near the facing. Once the applied load was released completely, the outward wall movements reduced confirming that the deformations were mainly contributed by the elastic deformation of the wall facing.

Loading of the saturated model behind the reinforced zone

Thereafter the saturated structure was loaded behind the reinforced zone. Once the loading intensity was increased to 160 kN/m$^2$, a crack appeared at the end of the reinforcement zone and at a loading intensity of 200 kN/m$^2$ the crack width had increased to about 5 mm. When the loading intensity was increased to 220 kN/m$^2$, the crack width had increased up to about 10mm and further loading was not possible. This is an indication of a catastrophic failure. The crack that developed behind the reinforced zone and the separation of the wall unit is depicted in Figure 9. Subsequently the failed model was carefully excavated to the bottom and the separation of the wall unit was seen to be continuing to the bottom level of the wall.

## TENSILE STRENGTH OF FRESH BAMBOO

It will be necessary to evaluate the tensile strength of the fresh bamboos used in the model wall construction. A number of specimens of length around 300 mm were prepared, specimens were numbered and initial dimensions were taken and a sample of ten was taken to evaluate the tensile strength in the fresh state. Tensile testing was to be conducted in the conventional tensile testing apparatus after doing some modifications. Two chucks were prepared to hold the two ends of the hollow cylindrical bamboo pieces when they are subjected to the tensile test. The prepared chucks were connected to the testing machine through a special arrangement. The arrangement is illustrated in Figure 10. A short steel piece of appropriate diameter was inserted inside the hollow bamboo at the two ends, with the view of minimizing any crushing due to the holding action of the chucks. The mid cross section of the bamboo specimens were reduced by carefully cutting off parts. The test results reveled that the tensile strength of fresh bamboos is around 300 MN/m$^2$.

## DURABILITY AND DETERIORATION OF BAMBOO REINFORCEMENTS

The results of the tensile tests, pullout tests and model tests illustrate that the bamboo reinforcements possess strengths and bond resistances that are comparable with or greater than that of the synthetic materials. Nevertheless, the major concern of the use of bamboos as reinforcing materials is their long term performance. Synthetic materials are manufactured under laboratory conditions with the use of various additives to ensure satisfactory long term performance. Natural material such as Bamboo could deteriorate when subjected to the elements of weather and suffer loss of strength in the long term.

Therefore it is necessary to evaluate the tensile strength of bamboos that are kept buried within the fill in a reinforced earth structure for a long time. Also, the possible shrinking of the bamboo reinforcements over a long period may lead to loss of contact between reinforcements and the soil, which in turn will cause a reduction in the bond coefficient $f_b$. As such, a test program was designed to evaluate the possible loss of tensile strength and the loss of dimensions when bamboos are buried within a fill in a reinforced earth structure for a long time.

Different types of chemicals can be used as preservatives to retard the deterioration of Bamboos. Laise (1989) outlined different methods that can be used to prolong the service period of Bamboos. In this project attempts were made to study the effectiveness of three chemicals; namely, Potassium Dichromate, Copper Sulphate and Cationic rapid setting emulsion (CRS 1) used in road construction. Bamboos that were treated with the chemicals were buried in an embankment together with the untreated samples. Two embankments were done; one each for a sandy fill and a lateritic fill.

For each method of treatment, seven bamboos were placed in each layer and there were a total of five layers. The embankment will be excavated at different periods of time and the bamboos in a given layer will be removed and subjected to tensile testing. It is proposed to remove the top layer after one year and the other layers at periods of 3 years, 6 years, 9 years and 12 years respectively. Once the bamboos are taken out their dimension will be taken to identify any shrinkage. Subsequently, the tensile strength will be evaluated using the arrangement used for the fresh bamboo. This testing procedure will provide a good picture of the deterioration of the bamboos with time and effectiveness of the preservatives.

## DESIGN OF BAMBOO REINFORCED EARTH RETAINING STRUCTURES

A rational design procedure was developed for the Bamboo reinforced earth retaining structures, based on the principles outlined in the preceding sections of this paper and making use of the data acquired in the pullout testing and tensile testing of Bamboo reinforcements. The procedure was outlined in detail by Kulathilaka (2000 (a)).

When the existing field structures were back analysed using the developed design procedure it was revealed that they possess safety factors on internal stability in the order of 7 to 8 and safety factors on external stability of 3 to 4.

## CONCLUSIONS

Internally stabilised earth retaining structures in the form of reinforced earth possess many advantages due to their flexible nature and ability to be constructed quickly without the use of special machinery. Also, they are usable immediately after the construction. The achievable wall height is unlimited and the rate of increase of cost with the height is much lower than for the gravity form of structures. As such they became very popular and many different innovative forms were developed. Most of the retaining structures constructed today to support highway embankments, bridge abutments etc. are of this form. For a developing country further advantages can be gained by the use of locally available material in these constructions.

The pull out studies on the bamboo reinforced meshes revealed that they have bond coefficient greater than 0.90 which is much greater than that reported for other synthetic forms of mesh reinforcements. Tensile tests conducted on bamboo materials showed that they posses tensile strengths greater than 300 $MN/m^2$, when they are fresh..

The model studies revealed that the bamboo reinforced earth retaining structures could be loaded to very high loading intensities within the reinforced zone without experiencing a catastrophic failure. The applied load itself help to increase the pullout resistance and the bamboos have a high tensile strength. As in the case of model anchored tyre earth retaining structures (Kulathilaka 2000 (b)), model reinforced earth structures had more resistance to overturning or sliding than an equivalent gravity retaining wall, when a load was applied behind the reinforced zone. The deformations seen in structures done with laterite fill were much smaller than in the case of sandy fill. This is an encouraging finding due to the lower cost of lateritic material.

The back analysis of existing field reinforced earth structures using the developed design method revealed that they possess very high safety margins. Thus it can be stated that they are not only inexpensive but are more stable than alternate gravity type earth retaining structures. If the deterioration of the bamboos with time can be controlled using an appropriate chemical they will have a very good potential as a reinforcing material in the earth retaining structures. The tests that are to be performed on buried reinforcements could reveal very useful information in this context.

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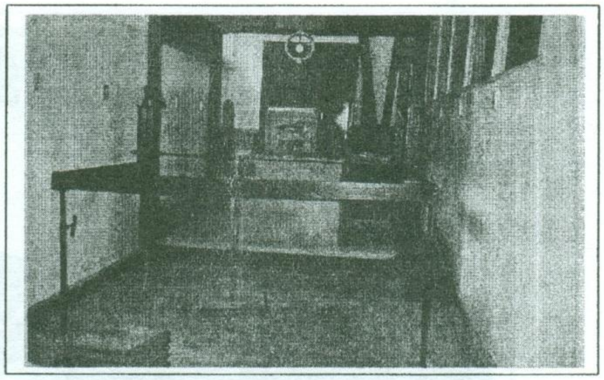


**Figure 3 - Determination of Pullout Resistance of Bamboo Meshes**

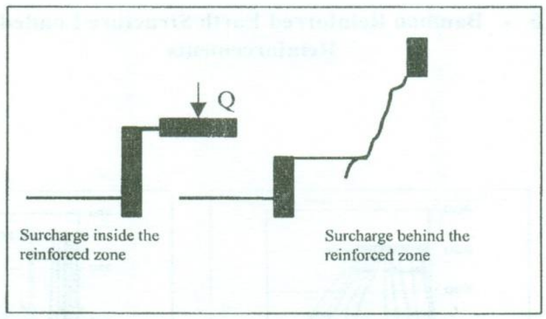



**Figure 4 - Different Loading Conditions on Reinforced Earth Structures**

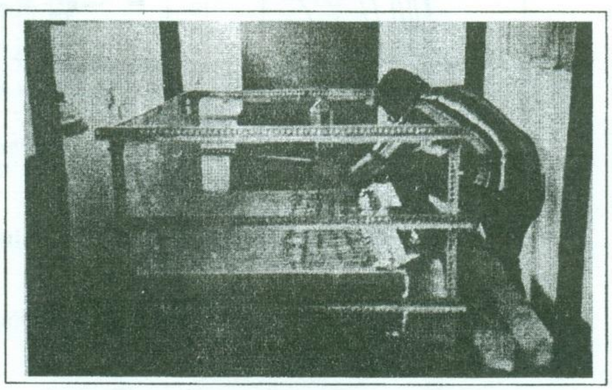


**Figure 5 - Construction of Model Bamboo Reinforced Earth Structures**

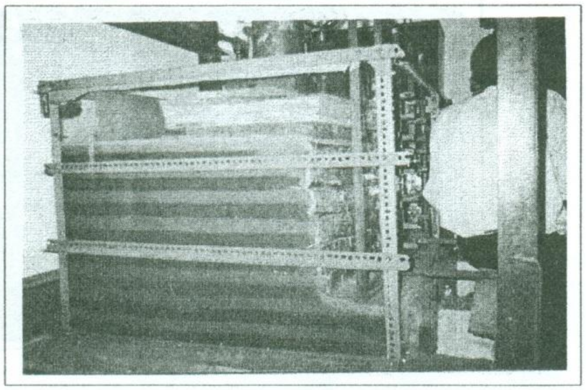
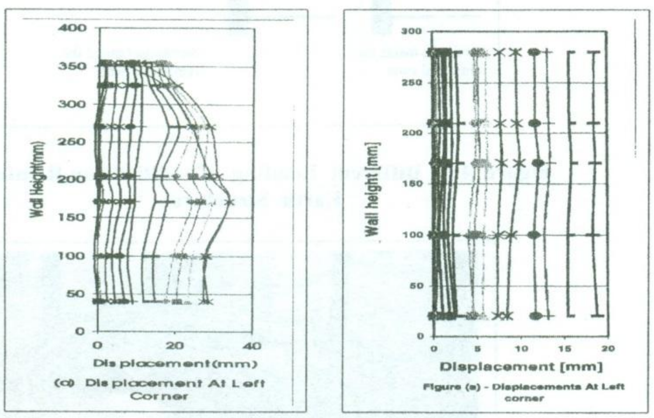


**Figure 6 - Bamboo Reinforced Earth Structure Loaded Within the Reinforcements**




**(a) Loading within reinforced zone** **(b) Loading behind reinforced zone**

**Figure 7 - Outward Movement of Wall Facing**

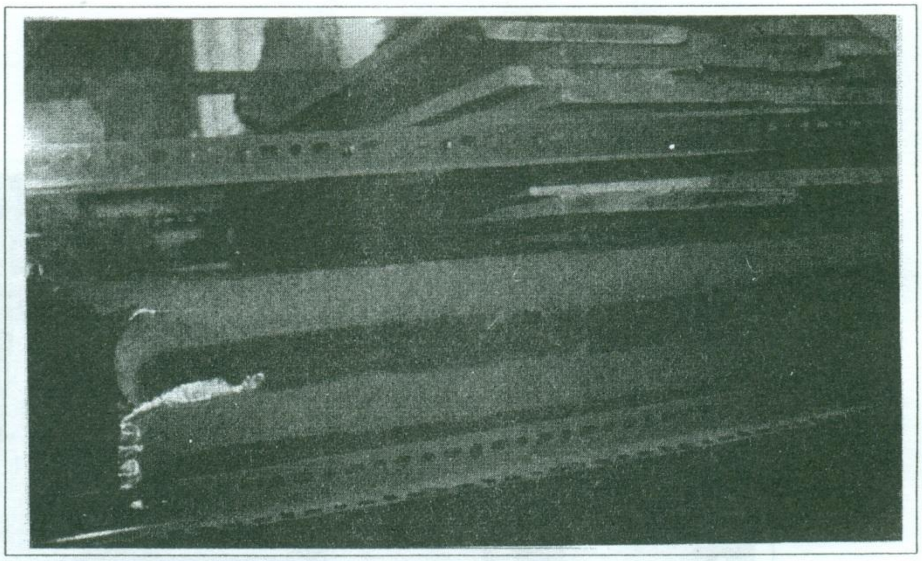


**Figure 8 - Separation of Wall Unit (Loading Behind Reinforced Zone)**

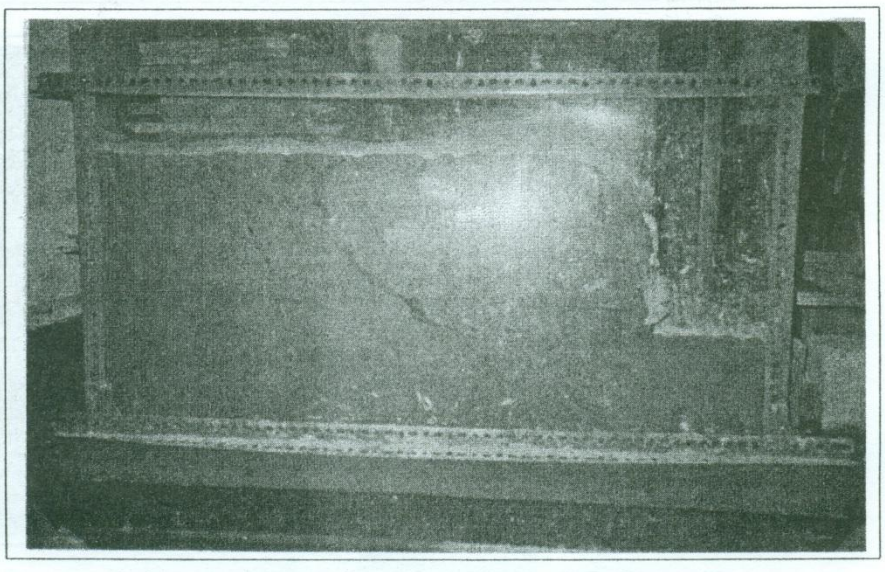
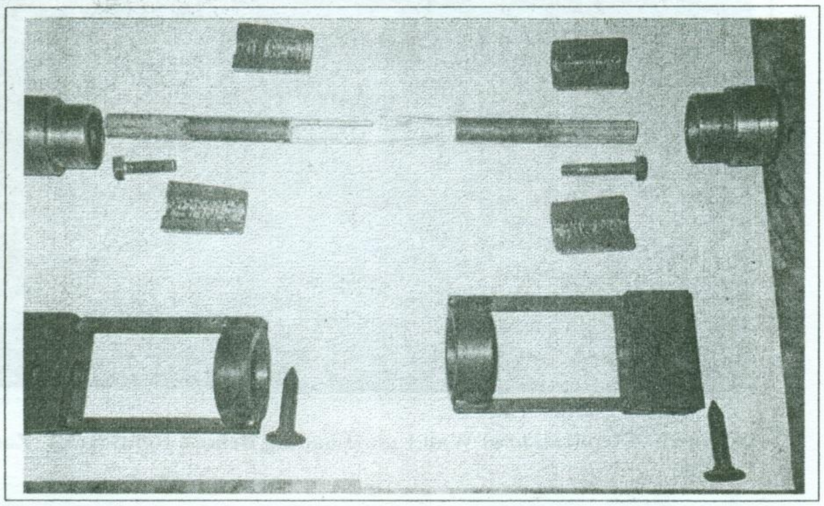


**Figure 9 - Separation of Wall Unit**
**(Saturated Model - Loading Behind the Reinforced Zone)**



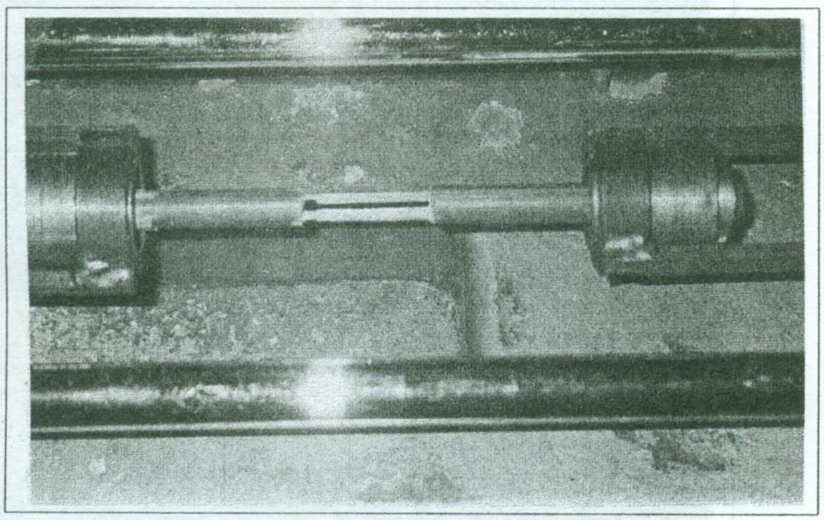


**Figure 10 - Determination of Tensile strength of Bamboo Reinforcements**