- Technical Paper -

FAILURE BEHAVIOR OF REINFORCED RAMMED EARTH WALLS SUBJECTED TO IN-PLANE HORIZONTAL LOADING

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ABSTRACT

The failure behavior of reinforced rammed earth walls is analyzed numerically for the case where rammed earth walls are subjected to in-plane horizontal loading. The effect of vertical compressive prestress is in particular investigated and analysis results are compared with test data in order to clarify the effective reinforcing method to resist earthquakes. The numerical simulation method used in this study is a combination of deformable plane elements and linkage elements in order to represent the brittle characteristics of rammed earth structures.

Keywords: rammed earth wall, prestress, failure, in-plane loading, simulation

1. INTRODUCTION

The statistics from UNCHS show that 40% of the world population lives in earthen dwellings and from the UNESCO's list of heritage show that 15% of the world cultural heritage is built with earth.

Rammed earth walls are formed by compacting damp soil, sometimes mixed with cement, between temporary formworks. Rammed earth is brittle and has low tensile strength and behaves catastrophically to earthquakes.

Some of the retrofitting methods considered were strengthening with reinforcing plates and fiber reinforcement. However, these methods seem to be labor intensive and difficult to install. Another method of retrofitting is that with the application of vertical compressive prestress.

In this study the effect of vertical compressive prestress on a wall with rammed earth mixed with cement will be analyzed with a numerical simulation method, Deformable Body Spring Model (DBSM) (see Zangmo et al.[1]), and results will be compared with the test data of Hamilton et al.[2] to clarify its effectiveness for a retrofitting method for rammed earth in seismic areas.

2. RAMMED EARTH

2.1 Construction

Rammed earth walls are formed by compacting damp soil between temporary forms. The moist soil is compacted in layers. The construction is done by hand compaction or mechanically with the use of construction equipment. The typical formwork arrangement used in construction is shown in Fig.1 and a typical rammed earth wall is shown in Photo.1.

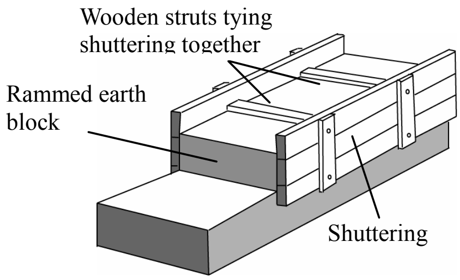

Fig.1 Formwork for rammed earth

2.2 Benefits of Rammed Earth

In the pursuit of sustainable development, earthen structures have tremendous potential in providing solutions for energy efficiency, human comfort, eco-architecture and cost effectiveness. Recent developments include wide adoption of stabilized compressed earth blocks and rammed earth structures reflecting the above advantages.

2.3 Concern of Rammed Earth

Rammed earth is very weak in shear and tension. Therefore when constructed in seismically active areas, the safety of such structures is a primary concern. For the new constructions, reinforcement, usually steel, is necessary, while for the existing structures, seismic retrofitting with wire mesh, artificial fabric sheet or timber elements are used. The installation of steel reinforcement is difficult and proper compaction around the reinforcing bars may not be reached. The installation of wire mesh, artificial fabric sheet and timber elements for retrofitting is also labor intensive.

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Photo.1 Typical rammed earth wall

A recently developed method to reinforce rammed earth walls is to use post-tensioned reinforcement (see Hamilton et al. [2]). This is convenient as the prestressing tendon is installed and stressed after the masonry is placed, thus reducing the labor intensive job of installing conventional bars and grout. In this type of reinforcing, the compressive strength of the structure has to be sufficiently large and it is important to make sure that the prestress applied does not exceed the compressive strength of rammed earth. Table 1 shows the advantages and disadvantages of rammed earth (see Yamin et al.[3], Maini [4]).

Table 1 Advantages and disadvantages of rammed earth

Advantages	Disadvantages
Environmentally friendly	Brittle (weak in shear and tension)
Low maintenance	Scatter in quality (depends on material properties and construction technique)
High insulation	
Thermal mass	
High fire resistance	Low water resistance
Insect proof	

3. NUMERICAL ANALYSIS METHOD

3.1 Deformable Body Spring Model

The numerical analysis model used in this study consists of modeling the material with deformable elements and two types of linkage elements (see Zangmo et al.[1]). This kind of modeling is selected to represent the brittle characteristics of rammed earth structures. Numerical models for dynamic analysis of brittle materials have been proposed by Cundall[5,6] and Shi[7]. The present model is considered suitable for static analysis of brittle materials. Linkage element type 1 is used for the connection between the deformable elements and linkage element type 2 for connecting the material to the boundary. A schematic diagram of a deformable body spring model is shown in Fig.2.

3.2 General Description of Material Model

The deformable elements are connected by

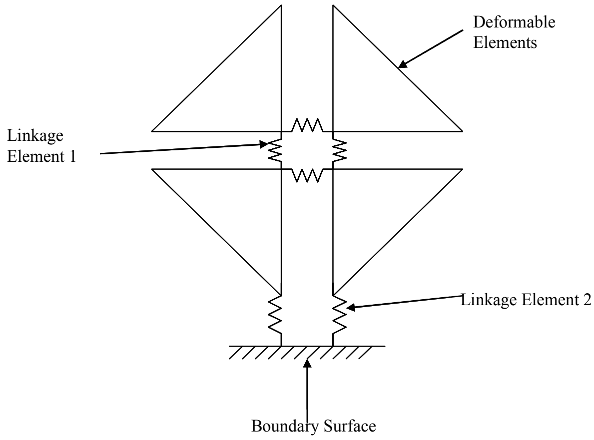

Fig.2 Schematic diagram of deformable body spring model

nonlinear springs in normal and tangential directions at the interface. The incremental relationship between the surface tractions and the relative displacements in normal and tangential directions of the interface of deformable elements is expressed as follows by a linkage element:

$$\boldsymbol{k}d\boldsymbol{u} = d\boldsymbol{f}\,; \qquad \boldsymbol{k} = \begin{bmatrix} k_n & 0 \\ 0 & k_t \end{bmatrix} \tag{1}$$

where $\boldsymbol{u} = [u_n, u_t]^{\mathrm{T}}$ and $\boldsymbol{f} = [f_n , f_n]^{\mathrm{T}}$ stand for relative displacements and the surface tractions at the interface respectively. The matrix $\boldsymbol{k}$ stands for the properties of the springs in the normal and tangential directions. The linkage element connecting deformable elements is shown in Fig.3. The local coordinates n and t represent the normal and tangential directions at the interface between deformable elements.

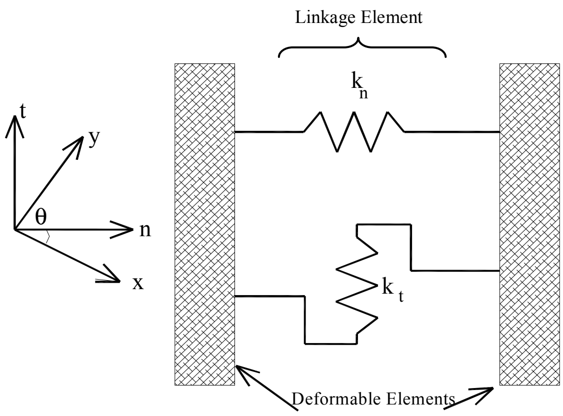

Fig.3 Linkage element connecting deformable elements

The nonlinear material properties of the component materials can be modeled by assuming that the matrix $\boldsymbol{k}$ which is a full matrix in general and non-symmetric in cases such as the phenomenon of friction or shear transfer. The normal stiffness and the tangential stiffness are reduced when the corresponding critical stress is reached. The number of stiffness

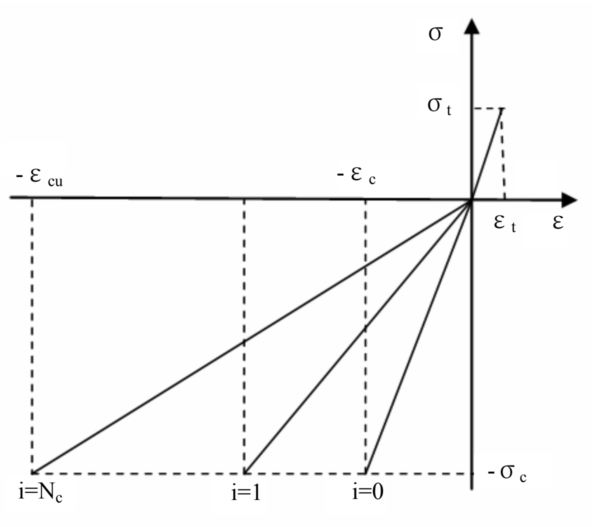

Fig.4 Modeling of material properties in the normal direction

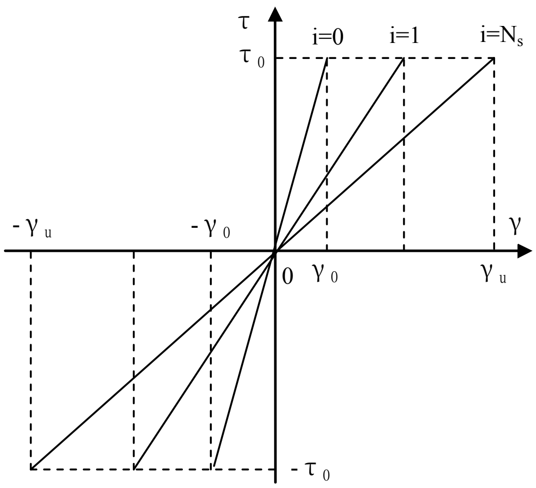

Fig.5 Modeling of material properties in the tangential direction

reduction is also specified. The material models in the normal and tangential directions for brittle materials are shown in Fig.4 and Fig.5. The details of this general description can be found in Tsubaki et al.[8].

3.3 Different Types of Material Behavior

Three different types of material behavior can be assumed as shown in Fig.6 (see van Mier[9]). The important material parameters for this modeling are the elastic modulus and the strength or the breaking threshold.

(a) Brittle type

The stiffness is reduced to zero once the strength is reached.

(b) Elastic-plastic type

A step-wise reduction of the stiffness with constant breaking threshold is considered.

(c) Elastic-softening behavior

A decreasing breaking threshold is considered in this case.

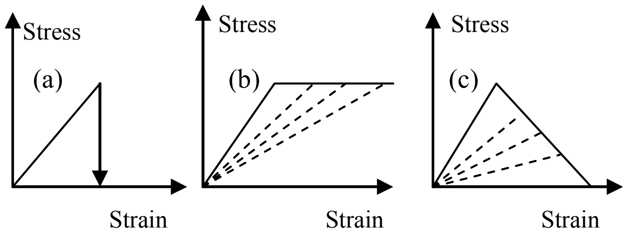

Fig.6 Different types of material behavior: (a) Brittle type, (b) Elastic-plastic type, (c) Elastic-softening type

3.4 Computational Algorithm

The analysis procedure is based on the secant analysis method. It consists of imposing unit displacements or forces and determining nodal displacements from the equilibrium equations. From the nodal displacements of each element, stresses for all the elements are determined. The flow of the secant

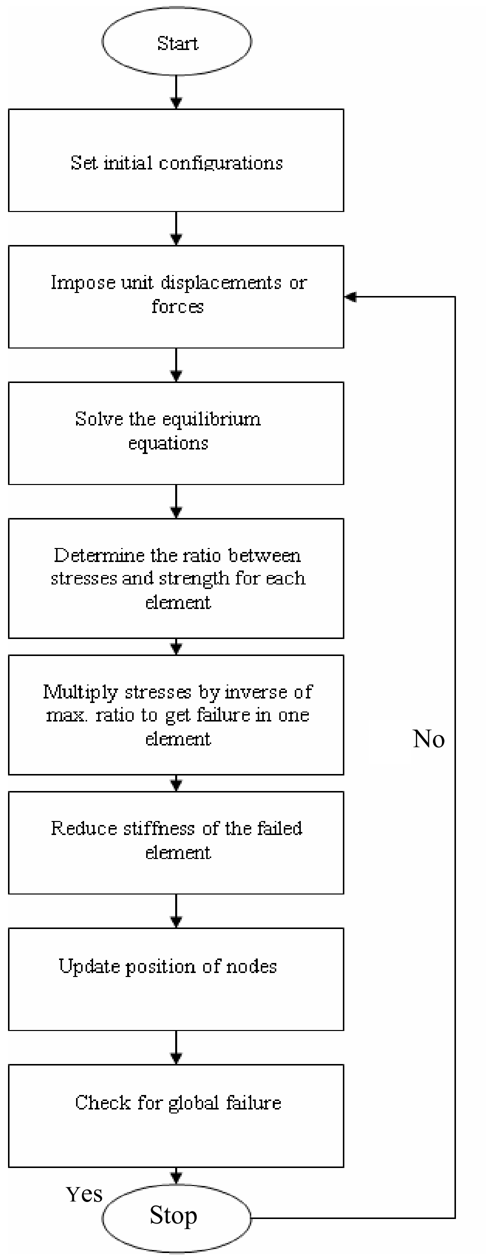

Fig.7. Flow chart of secant analysis method

analysis method is shown in Fig.7. The details of this analysis method can be found in Abdeen et al.[10] and Vulpe et al.[11], and Ogura et al.[12].

The effect of prestress is implemented in the increase of the tensile strength of the rammed earth material considering the direction and the magnitude of the prestressing force.

4. NUMERICAL SIMULATION

4.1 Outline of Experiment

Hamilton et al. [2] constructed rammed earth walls in the laboratory. The earth used for the construction of the walls was screened, engineered soil, which was mixed at a rate of approximately 8% water and 3% Type I Portland cement to make soil-cement mixture. The mixture was placed in layers of 20cm thick and compacted to 13cm thick. The average compressive strength of rammed earth is 6.3MPa. The density is 2.002. Two steel tendons were used and each of them was post-tensioned to 124.6kN. The post-tensioning bar has diameter of 17.5mm, yield strength of 690MPa and ultimate strength of 840MPa. The walls were supported as a cantilever with top unrestrained. The loading was cyclic and fully reversed to examine the ability of the walls to undergo large displacements that might follow an earthquake. The wall height is 2235mm, the wall width is 1828mm, the wall thickness is 406mm and the distance between the post-tensioning rods is 914 mm. Concrete base and cap of 89mm thickness with concrete compressive strength of 28MPa was used at the bottom and the top of the wall (see Fig.8).

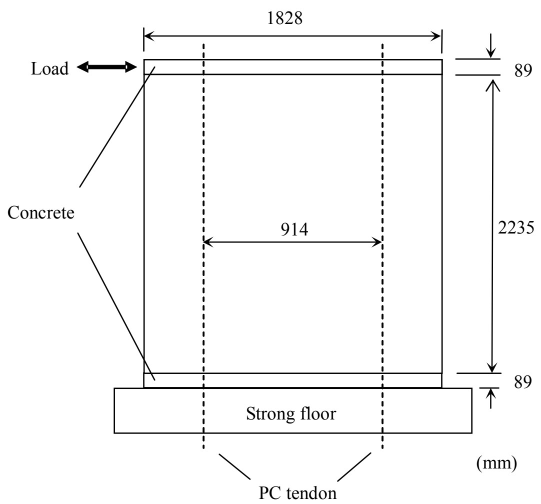

Fig.8 Specimen and loading

4.2 Failure Mode

The wall failed with a horizontal crack developing at the bottom part of the specimen and extending as the loading continued. The failure mode is shown in Fig.9. The cracking appeared at the base of the wall first and then a horizontal crack at about 20cm from the bottom extended as the load increased. There was no other major crack in the specimen.

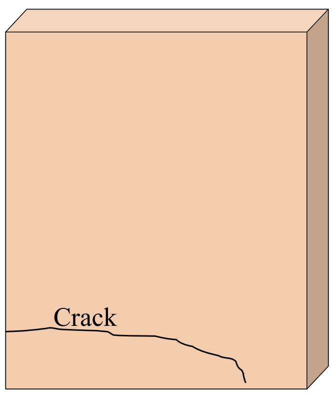

Fig.9 Failure mode

4.3 Structural Modeling

The structural discretization is done by using a combination of linkage elements and deformable elements as shown in Fig.10. Deformable elements are supported and connected by linkage elements in this model. The element discretization of the wall is shown in Fig.12. The top layer represents the concrete loading block part attached to the rammed earth wall specimen. The steel tendons were represented by superimposed deformable elements taking into account the area ratio between the steel tendon and the whole rammed earth wall. The whole rammed earth was fixed to the bottom boundary by the linkage element 2.

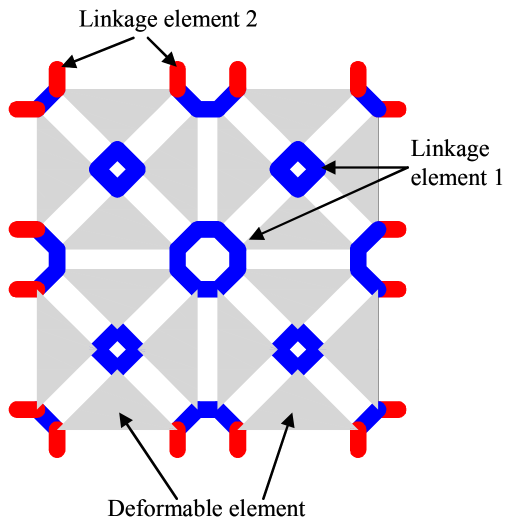

Fig.10 Element discretization

4.4 Material Parameters

The material parameters used for the deformable elements and linkage elements are shown in Table 2. The analysis was done for a rammed earth wall of unit thickness (1mm). Therefore, spring constants of linkage element are of the value for unit thickness of the wall. For the constants of the steel tendon, the area ratio of steel tendon to the whole cross-sectional area of the wall was factored to determine the equivalent elastic modulus.

Rammed earth is modeled as a brittle material (see Figs.4, 5, 6), i.e., brittle in tension, elastic-plastic in compression and shear. The steel tendon is modeled as an elastic-plastic material. The concrete cap is modeled as an elastic material because it is strong and stiff enough not to fail during loading.

The elastic constants and the tensile strength of rammed earth are not given as test data. Therefore the elastic constants of rammed earth were first estimated from the test data of displacement. The tensile strength of rammed earth represented by the normal strength of linkage element 1 was estimated from the test data of cracking load. These values were adjusted and identified through the simulation. The normal strength and the tangential strength of linkage element 1 for rammed earth are obtained as a product of strength and the cross-sectional area of element. The number of stiffness reductions N_c, N_s in both compression and shear of rammed earth was set as 3 (see Figs.4, 5).

The material constants of concrete cap and steel tendon were set from the information of test results adjusting them to the value of unit thickness.

Other material constants were identified by the comparison between the simulation results and the test results.

The linkage element 2 was assumed elastic and the stiffness was set sufficiently large from the information of test results that the base of the wall did not slide due to the applied horizontal load.

Table 2 Material parameters

Material property	Value
Deformable elements	
1) Rammed earth	
Elastic modulus	1000MPa
Poisson ratio	0.2
2) Concrete	
Elastic modulus	45GPa
Poisson ratio	0.2
3) Steel	
Equivalent elastic modulus	8GPa
Poisson ratio	0.3
Linkage elements	
1) Linkage element 1	
Normal spring constant	1.0×10^7N/mm
Tangential spring constant	1.0×10^7N/mm
Normal strength	0.1MPa
Tangential strength	0.6MPa
2) Linkage element 2	
Normal spring constant	2.0×10^7N/mm
Tangential spring constant	2.0×10^7N/mm

4.5 Simulation of Rammed Earth Wall under In-Plane Shear

The rammed earth wall with the same dimensions as the specimen of Hamilton et al.[2] is modeled with Deformable Body Spring Model and analyzed with in-plane shear load. The load- displacement relationship up to the cracking load is plotted and compared with the test results as shown in Fig.11. The zigzag behavior

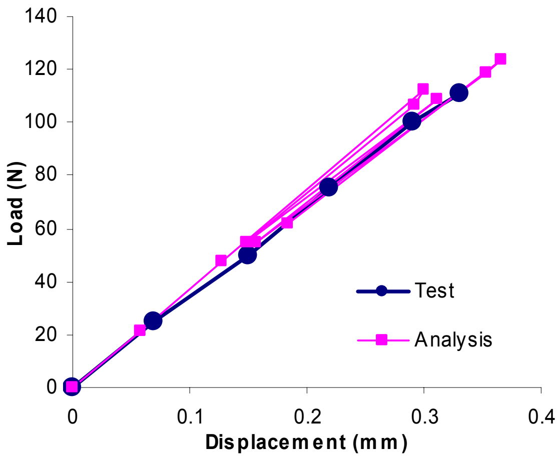

Fig.11 Load-displacement relationship

beyond the cracking load is due to the nature of the secant analysis method, representing the unstable behavior accompanied with the tensile failure. The large zigzag behavior which is not observed in the actual test result is due to the size of elements. The displacement and stress distribution diagram at two different stages are shown in Fig.12. The stress plotted is the first stress invariant of stresses. The stress concentration at the crack tip and the intense compressive stress at the compression zone are observed. In this simulation the effect of self-weight was neglected for the sake of simplicity.

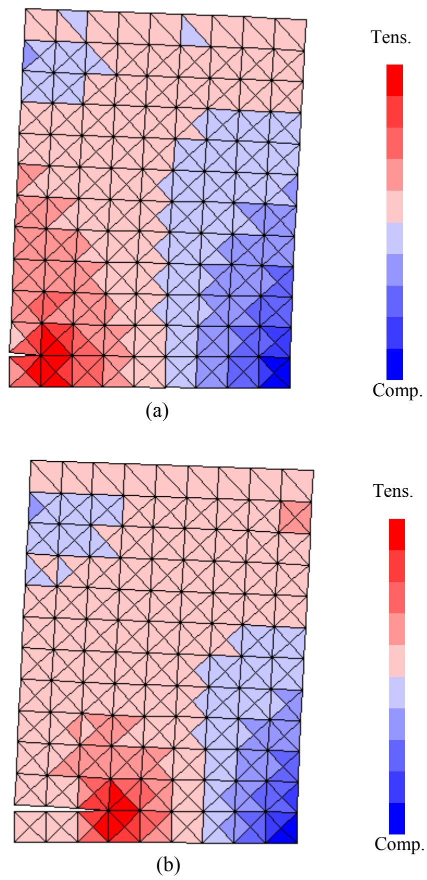

Fig.12 Displacement and stress distribution diagram: (a) Early stage, (b) Final stage

4.6 Effect of Prestress

The rammed earth wall was analyzed with different levels of prestress with the same material constants and the analysis conditions as those used in the previous simulation of rammed earth wall. The relation between the cracking load and the total prestressing force is shown in Fig.13. It is confirmed that the cracking load increases with the amount of prestress.

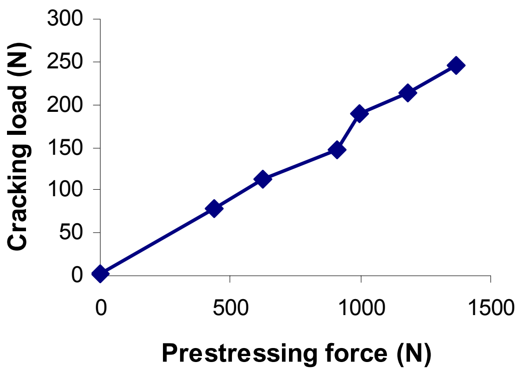

Fig.13 Relationship between cracking load and prestress

5. CONCLUSIONS

The failure behavior of rammed earth wall subjected to in-plane horizontal loading was investigated with an emphasis on the effect of the prestress. The following conclusions were obtained from the present study.

(1) The analytical model used in this study, a combination of deformable plane elements and linkage elements, was effective to model and express the brittle characteristics of rammed earth structures.
(2) The failure behavior accompanying the horizontal cracking was obtained by analysis, which is in agreement with the test data.
(3) The effect of prestress on the cracking load of rammed earth wall has been clarified.

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