Seismic Retrofitting of Rammed Earth Walls with Prestressing

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1. INTRODUCTION

Rammed earth walls are formed by compacting damp soil in temporary formworks. Rammed earth is environmentally friendly and sustainable. According to the statistics from the UNCHS (United Nations Centre for Human Settlements), 40% of the world population lives in earthen houses and from UNESCO (United Nations Educational, Scientific and Cultural Organization)'s list of heritage, 15% of world cultural heritage is built with earth.

Rammed earth has very low shear strength and negligible tensile strength, which makes it susceptible to catastrophic brittle failures in case of earthquakes [1]. In order to strengthen the rammed earth walls against seismic loads, various ways of reinforcing have been suggested, such as putting vertical and horizontal timber or cane elements, inserting steel rods, and using wire mesh with plaster.

More recently, the prestressed rammed earth walls have been considered as an effective and easy way of retrofitting or reinforcing against earthquake loads [2]. The prestressing force applied acts as a vertical compressive load which helps in withstanding against the horizontal forces applied due to earthquakes.

In this study the effect of vertical compressive prestress on a rammed earth wall made of natural mud mixed with cement is analyzed using a numerical analysis model called Deformable Body Spring Model [3] and the results are compared with the relationship obtained with the beam theory.

2. NUMERICAL ANALYSIS METHOD

2.1 DEFORMABLE BODY SPRING MODEL (DBSM)

Numerical models for dynamic analysis of brittle materials have been proposed by Cundall[4,5] and Shi[6]. For a static analysis of brittle materials the disc element methods have been proposed for two-dimensional problems and three-dimensional problems by Abdeen et al.[7] and Vulpe et al.[8]. An application to a brittle material like porous concrete has also been proposed by Ogura et al.[9].

The deformable body spring model which is used in this study is for a static analysis of brittle materials [3]. The material is modeled with deformable elements and two types of linkage elements. The use of deformable elements instead of rigid body elements enables the calculation of stress and strain more rationally in those elements. This is the main difference between the Deformable Body Spring Model and the previous models. Linkage element 1 is used for connecting the deformable body elements and linkage element 2 is for the connection of the brittle material to the boundary. This kind of modeling is selected to represent the brittle characteristics of the rammed earth. This model is considered suitable for static analysis where cracking, opening of cracks and sliding along crack surfaces are expected. A schematic diagram of the Deformable Body Spring Model and the linkage element connecting deformable elements are shown in Fig.1 and Fig.2.

2.2 GENERAL DESCRIPTION OF MATERIAL MODEL

The deformable elements are connected at their nodes by nonlinear springs in normal and tangential directions at the interface between deformable elements. 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 $\boldsymbol{u} = [u_n, u_t]^T$ and $\boldsymbol{f} = [f_n, f_n]^T$ respectively stand for the relative displacements and the surface tractions at the interface between deformable elements. The matrix $\boldsymbol{k}$ stands for the properties of the springs in the normal and tangential directions. The local coordinates n and t represent the normal and tangential directions at the interface between 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 a case 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 reduction is also specified. The material models in the normal and tangential directions for brittle materials are shown in Fig.3 and Fig.4. The details of this general description can be found in Tsubaki et al.[10].

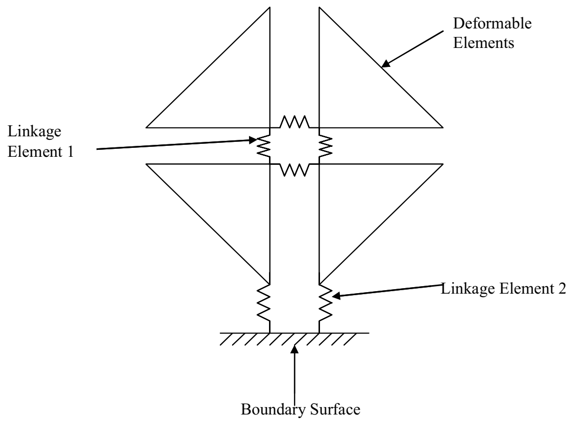

Fig. 1 Schematic diagram of deformable body spring model

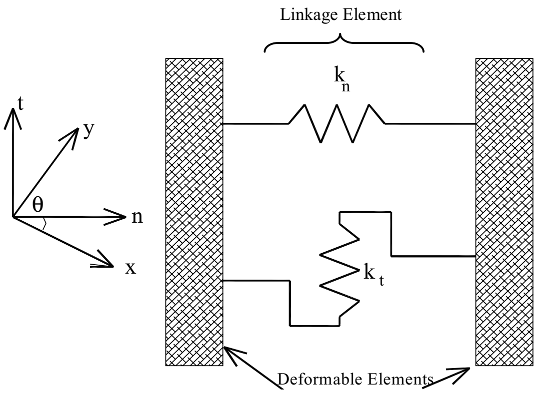

Fig. 2 Linkage element connecting deformable elements

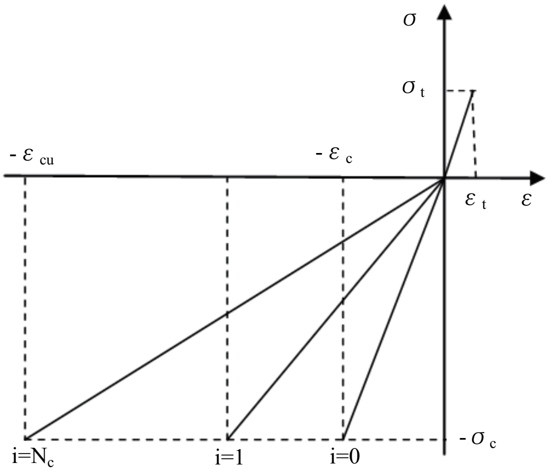

Fig. 3 Modeling of material properties in the normal direction

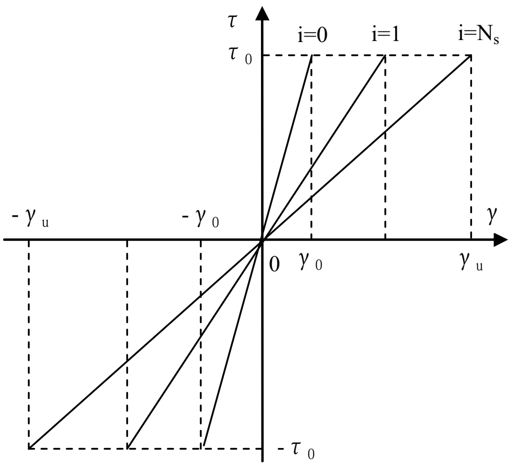

Fig. 4 Modeling of material properties in the tangential direction

2.3 COMPUTATIONAL ALGORITHM

The analysis procedure is based on the secant analysis method. The flow of the secant analysis method is shown in Fig.5. The details of this analysis method can be found in Abdeen et al.[7], Vulpe et al.[8], and Ogura et al.[9]. It consists of the following steps.

(1) Impose unit displacements or forces to the structure in a consistent way with the given loading and boundary conditions.
(2) Solve the equilibrium equations with the secant stiffness.
(3) Calculate the unknown nodal displacements from the equilibrium equations.
(4) From the nodal displacements of each element, calculate stresses for all the elements.
(5) Determine the ratio between the stress and the strength for each element.
(6) Multiply stresses by the inverse of the maximum ratio obtained in Step (5) to get the failure in the element with the maximum ratio.
(7) Reduce stiffness of the failed element according to the given stress-strain relationship.
(8) Update the positions of nodes in case of large displacement.
(9) Check if the global failure occurs.
(10) Go to Step (1) until the global failure occurs.

3. EXPERIMENTAL WORK

3.1 OUTLINE OF EXPERIMENT

Hamilton et al. [2] constructed rammed earth walls in the laboratory to investigate the effectiveness of prestressing on increasing the seismic capacity of a rammed earth wall to both out-of-plane (flexural) loading and in-plane (shear) loading.

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 12.0MPa. The density is 2002.3kg/m^3.

One steel tendon was used and 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 bar was placed inside 38mm-diameter PVC pipe.

Concrete base and cap of 89mm thickness with concrete compressive strength of 28MPa were used at the bottom and the top of the wall. The rammed earth wall was put on the concrete base and the concrete cap was placed on the top of the rammed earth wall. After the concrete cap was placed, the tendon was pulled from the top of the specimen, which allowed the tendon to be stressed after the wall was constructed.

The wall height is 2972mm, the wall width is 406mm, the wall thickness is 1219mm. 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. A hydraulic actuator of a closed-loop servo-controlled hydraulic system was used to displace the top of the wall about the weak axis.

Cracking of the wall occurred at a horizontal displacement at the loading point of approximately 5mm and the horizontal load of 6.7kN, and became visually apparent at a horizontal displacement of approximately 19mm. The position of the crack was at the top between the concrete base and the rammed earth wall.

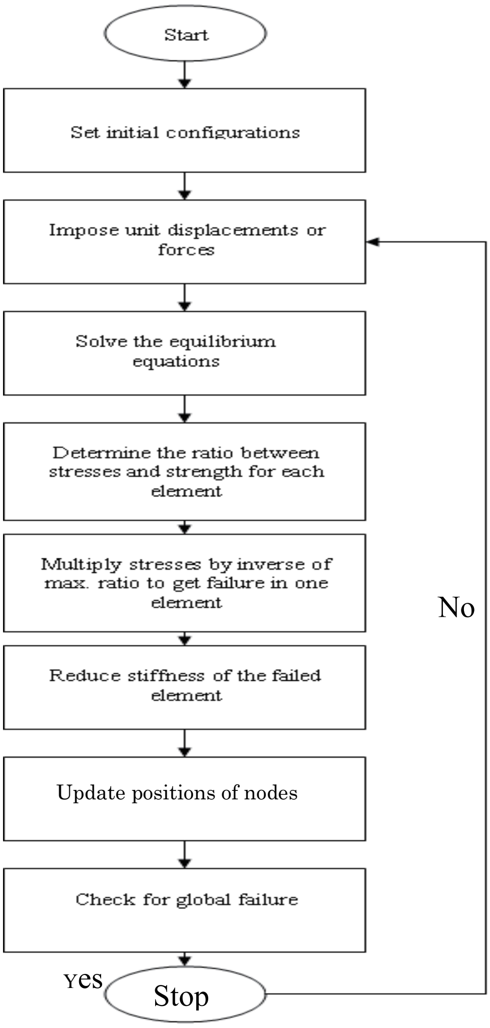

Fig.5 Flow chart of secant analysis method

3.2 LOADING AND FAILURE

The walls were tall and narrow referred to as flexural walls and were subjected to out-of-plane flexure. The load was applied in the direction perpendicular to the plane of specimen shown in Fig.6. The first crack appeared near the interface between concrete base and the rammed earth. The load history showed very little energy dissipation in the hysteresis loops indicating

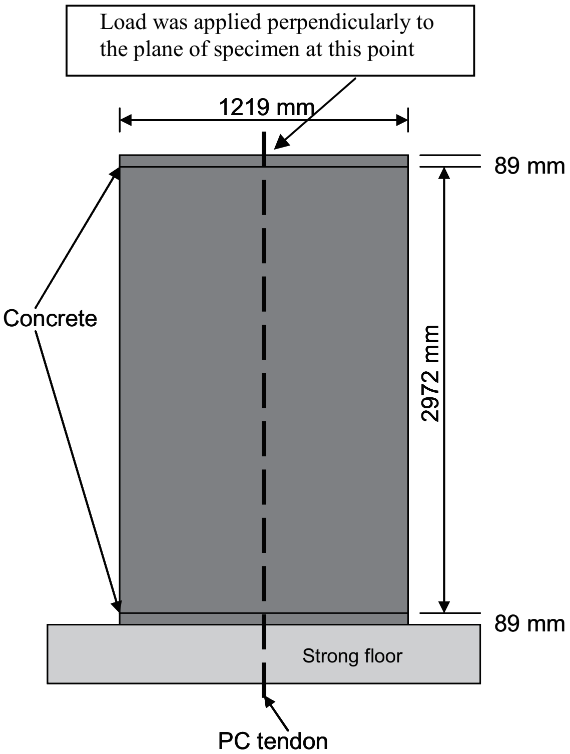

Fig. 6 Rammed earth specimen

little damage to rammed earth or the post-tensioning tendon.

Four walls were tested altogether and it was shown that the compressive failure or crushing occurs near the base when there is a non-uniform material distribution. The wall specimen examined in this study did not show such a localized compressive failure.

4. NUMERICAL ANALYSIS

4.1 STRUCTURAL MODELING

The structural discretization is done by using a combination of linkage elements and triangular deformable elements. Deformable elements are supported and connected by linkage elements in this model. The schematic element discretization of the wall is shown in Fig.7. In this figure the gap between the deformable elements is exaggerated to show the allocation of the linkage elements clearly. In the actual element discretization the gap between the deformable elements is of zero thickness.

With this way of element discretization the cracking in the horizontal direction, that in the diagonal direction and that in the vertical direction can be represented. The use of linkage elements along the interface between deformable elements allows not only the cracking of opening mode but also the cracking in the sliding mode which is considered important in case a brittle material like rammed earth is examined.

In the element discretization of the rammed earth wall shown in Fig.6, the concrete loading block part attached to the rammed earth wall specimen is represented by a layer of deformable elements. The steel tendon is represented by superimposed deformable elements taking into account the area ratio between the steel tendon and the cross-sectional area of triangular elements.

The overall rammed earth wall is divided into 11 equal layers in the vertical direction and 9 equal layers in the horizontal direction. The height of each horizontal layer is 270mm, and the width of each vertical layer is 45mm. The detail of the element discretization of each layer is the same as the discretization pattern shown in Fig.7 and it is shown in Fig. 8 schematically. The top horizontal layer represents the concrete cap.

The whole rammed earth is fixed to the bottom boundary by a number of linkage elements 2.

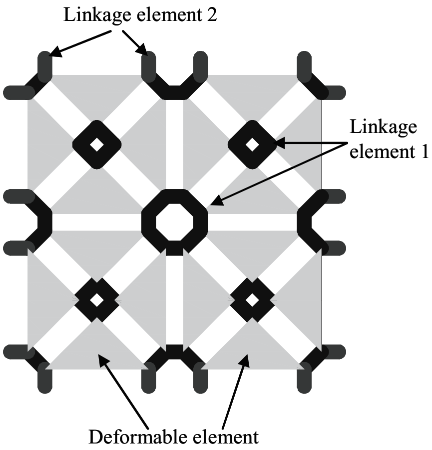

Fig. 7 Detail of elements used in DBSM

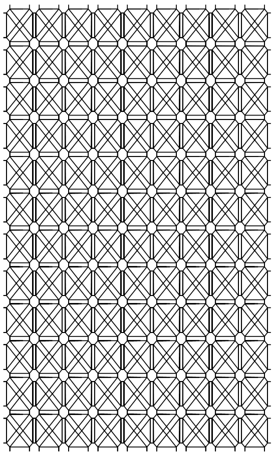

Fig.8 Discretization of wall

4.2 MATERIAL PARAMETERS

The material parameters used for the deformable elements and two types of linkage elements are shown in Table 1. The analysis is 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 cross-sectional area of element representing steel tendon is factored to determine the equivalent elastic modulus.

Rammed earth is modeled as a brittle material, brittle in tension, elastoplastic in compression and shear (see Fig.3 and Fig.4). The steel tendon is modeled as an elastoplastic material. The concrete cap for applying load is modeled as an elastic material because it is strong and stiff

Table 1 Material properties

Material property	Value
Deformable elements	
1) Rammed earth	
Elastic modulus	1200MPa
Poisson's ratio	0.2
2) Concrete	
Elastic modulus	27GPa
Poisson's ratio	0.2
3) Steel	
Equivalent elastic modulus	0.79GPa
Poisson's ratio	0.3
Linkage elements	
1) Linkage element 1	
Normal spring constant	2.5x10 ^{7}N/mm
Tangential spring constant	2.5x10 ^{7}N/mm
Normal strength	0.51MPa
Tangential strength	7.0MPa
2) Linkage element 2	
Normal spring constant	2.5x10 ^{7}N/mm
Tangential spring constant	2.5x10 ^{7}N/mm

enough not to fail during loading.

The elastic constants and the tensile strength of rammed earth are not given in the test data. Therefore the elastic constants of rammed earth are first estimated from the test data of displacement. The tensile strength of rammed earth represented by the normal strength of linkage element 1 is estimated from the test data of cracking load taking into consideration the self weight of the wall. These values are 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 is set as 3. In case the material behavior is more ductile the number of stiffness reduction may be set larger. The material constants of concrete cap and steel tendon are set from the information of test results adjusting them to the value of unit thickness. Other material constants are identified by the comparison between the simulation results and the test results.

The linkage element 2 is assumed elastic and the stiffness is set sufficiently large from the information of test results that the base of the wall did not slide due to the applied horizontal load. The effect of prestress is implemented as an increase in the tensile strength of the rammed earth material considering the direction and magnitude of the prestressing force.

4.3 SIMULATION OF RAMMED EARTH WALL UNDER OUT-OF-PLANE FLEXURE

Rammed earth is weak in tension and the failure behavior after cracking is brittle. Therefore, the cracking is considered as the critical state of rammed earth structures. After cracking, rammed earth structures are expected to enter the condition of disintegration. From this point of view, the condition for cracking is mainly investigated in this study. Two types of failure modes of cracking are considered for rammed earth, i.e., the opening mode as in the case of flexural cracking and the sliding mode as in the case where the effect of shear is significant along a weak plane. Because rammed earth is constructed layer by layer, it is expected that a weak plane exists in the rammed earth structure. The analysis method used in this study can be applied to both cases. In the analysis the effect of self-weight is considered.

(1) Deformation and failure mode

The rammed earth wall with the same dimensions as the specimen of Hamilton et al. [2] is modeled with the Deformable Body Spring Model and analyzed under out-of-plane flexural loading. In the experiment the loading is reversed cyclic. In this study, however, the monotonic loading is applied to investigate the initial cracking behavior considering the effect of prestress.

The load-displacement relationship up to the cracking load is almost linear due to the nature of the present analysis method. The cracking in the opening mode is detected when the normal spring of the linkage element 1 fails in tension. The crack extension is represented by the successive failure of the same kind in the linkage elements.

From the analysis results, it becomes clear that for the range of prestressing force examined in this study and for the assumption of homogeneous condition of wall the cracking is of opening mode and sliding along a crack does not occur, although experimental results show that sliding occurs in the bottom part of wall in case of having weak part. This result may also depend on the assumed shear strength of rammed earth. The localized compressive failure observed in the experiment does not occur either.

The horizontal cracking started at the point near the surface of the bottom layer of linkage-element 1 in the rammed earth specimen. The crack extended horizontally by the subsequent loading. This cracking behavior is in agreement with the experimental result described before. The cracking load obtained by the analysis is shown in Fig.9.

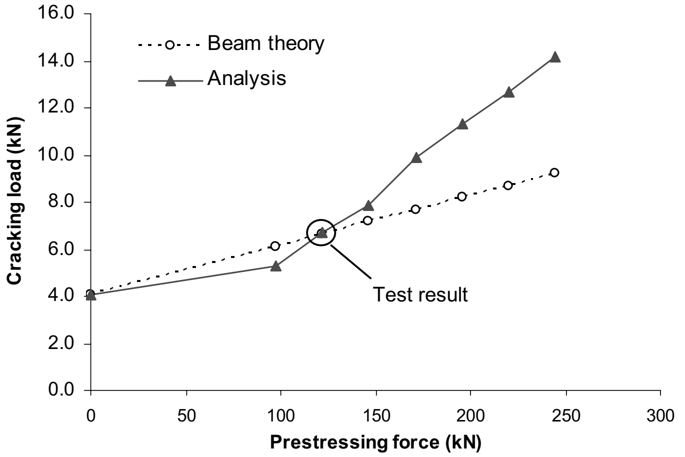

Fig.9 Relationship between cracking load and prestressing force

(2) Effect of prestress

The rammed earth wall shown in Fig.6 is analyzed with different levels of prestress with the same material constants and the analysis conditions. The relationship between the cracking load and the total prestressing force, and the comparison with the same relationship obtained by using the beam theory is shown in Fig.9. The prestressing force and the cracking load are the total values for the actual test specimen of the rammed earth wall.

It is confirmed that the cracking load increases with the amount of prestress. When a total of 125kN prestressing force is used the cracking load is increased by more than 60%, from 4.1kN (zero prestress) to 6.7kN.

As it can be seen from Fig. 9, from the beam theory, the cracking load increases linearly with the amount of prestressing force, the tendency of which is in agreement with the relationship obtained from the analysis. The difference between the results of the analysis and the beam theory is considered due to the two-dimensional effects and the action of unbonded tendon.

The amount of prestress for seismic retrofitting should be determined by considering the magnitude of earthquake considered in the design stage. The range of the prestressing force examined in the present study covers the earthquake which may be considered large enough from the past earthquake data.

5. CONCLUSIONS

The effect of prestress on the cracking load and the failure mode of rammed earth wall subjected to out-of-plane or flexural loading is investigated by using a discrete numerical analysis method called the Deformable Body Spring Model method. The cracking state which is considered as the most critical state for a rammed earth structure has mainly been examined in this study. From the results of the present study the following conclusions can be drawn.

(1) It is confirmed that the cracking load increases with the increase of prestressing force in the opening mode of cracking in case of a rammed earth wall with a brittle material.

(2) The magnitude of prestressing force may be determined from the assumed earthquake considering the strength of rammed earth.

(3) From the previous experimental work, the failure mode of rammed earth wall may become sensitive to the scatter and the distribution of the material properties. In case of non-uniform distribution a localized failure which may result in the failure in the early stage of loading may occur. The analysis method used in the present study is suitable for this kind of case.

(4) The appropriateness of the present analysis method to rammed earth wall is confirmed by observing the results on the cracking of the rammed earth wall. Cracking is considered as the most critical state for a rammed earth structure because cracking leads to the disintegration of such a structure. From this point of view, therefore, it is considered that the most essential part of the failure behavior of a rammed earth structure has been examined and the appropriateness of the analysis method has been confirmed in this study.

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