



## **Modelling the behavior of rammed earth structures**

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## **SUMMARY**

Earth has been widely used through ages as a suitable material for building construction. For example, millions of buildings made with earth are listed in France (Michel & Poudru F 1987). Rammed earth is one of the represented building technique in this list. As no regulation exists for rammed earth structures in France, the owners of such structures are helpless at the time when repairing damages appearing in any aging heritage. This work is part of a national research project devoted to the study of construction building involving earth. In particular, both monotonous and cyclic mechanical tests were carried out on some representative materials used in France for rammed earth buildings. In this paper, a numerical modelling of these experiments is provided. An elastoplastic constitutive law is developed for modeling the behavior of rammed earth. It is based on a hierarchical approach of the modeling in relation to the information available to identify the set of model parameters. This model is based on a pre-existing elasto-plastic model developed for soils.

## **1. INTRODUCTION**

Rammed earth is a structure made by compacting moist earth (ie: sand, clay, gravel) between temporary formworks. The formworks are then removed and the rammed earth dries given birth to an extremely strong and long-lasting structure. This construction technique is currently becoming more popular because it meets the requirement of sustainable development, requires low embodied energy for construction and only processes local material. Passed studies showed that rammed earth walls contribute to the inner comfort of the occupants (Windstorm & Schmidt 2013).

However, as no standards exist for rammed earth structures in France, the owners of such structures are helpless at the time when have to repair if damages appear. The national earth building design standards from Australia, New Zealand, USA and Zimbabwe can be helpful to develop a French design standard suitable for the materials and construction building in force on the French territory.

This work is part of a national research project devoted to the study of construction building involving earth. During the project, different experiments were carried out on some representative materials used in France for rammed earth buildings. In this paper, a numerical modelling of these experiments is performed. A hierarchical elastoplastic constitutive law is developed for modeling the behavior of rammed earth. The sophistication of the modelling is related to the information available to identify the set of model parameters. This model derives from an existing model denoted CJS formerly developed in Ecole Centrale de Lyon for granular soils. The basic (first) level of the model, CJS-1 is similar to a Mohr-Coulomb model but with a failure surface that is continuously differentiable. The second level (more complex model) CJS-2, is an elastoplastic model with an isotropic hardening.

## **2. METHODOLOGY**

To reach the goal, this work is based on experiments on rammed earth as reference for model calibration. Here, a compression test on rammed earth, which shows many features of concrete behaviour is used.

## 2.1 Experiment

The experiment was performed by Champire et al. (2016) in École Nationale des Travaux Publics de l'État (ENTPE). It corresponds to an unconfined compression test where image processing allowed the axial deformation field to be measured. To validate the measurements, the deformations were also measured by means of non-contact sensors in both the axial and radial directions at sample mid-height. The maximum volumetric contraction state corresponds to a stress roughly equal to  $0.85 \cdot f_c$  ( $f_c$  being the maximum compression resistance). At this state, the rate of creation of micro-cracks compensates the rate of possible undamaged elastic contraction.

## 2.2 CJS Model

In this work, a constitutive model for rammed earth was created on the basis of an existing elasto-plastic "CJS" model for soils. CJS stands for Cambou-Jafari-Sidoroff who are the authors of this latter model (Dubujet 1992, Purwodihardjo 2004). The most interesting idea of this model lies in the existence of different levels (sophistication) of the constitutive equations depending on the amount of information available to identify the model parameters. Herein, two basic plastic mechanisms consisting in a tensile and shear yield surface are used. The tensile yield surface is also a failure surface but the shear yield surface can exhibit hardening. In the case of rammed earth, the following constitutive model is proposed for the two levels of modeling CJS-1 and CJS-2.

### 2.2.1 Elastic mechanism for CJS-1 and CJS-2

The elastic deformations are computed according to Hooke's law:

$$\dot{\epsilon}_{ij}^e = \frac{\dot{S}_{ij}}{2G} + \frac{\dot{I}_1}{9K} \delta_{ij} \quad (\text{eq.1})$$

with  $S_{ij}$  is the deviatoric stress tensor and  $I_1$  is the 1<sup>st</sup> invariant of the stress tensor. Here, the elastic properties ( $G$  and  $K$ ) are taken as constant which leads to a linear elasticity. These elastic parameters that are related to the Young modulus and the Poisson ratio can be identified from a compression test.

### 2.2.2 Plasticity for CJS-1 and CJS-2

#### a. Tensile yield surface

$$f^t(\sigma_3) = \sigma_3 - T_r \leq 0 \quad (\text{eq.2})$$

with  $\sigma_3$  is the minor principal stress and  $T_r$  is a model parameter which characterizes the tensile strength of the material. Once  $\sigma_3$  reaches  $T_r$ , tensile failure occurs.

#### b. Shear yield surface

$$f^d(\sigma_{ij}, R, X_{kl}) = q_{II} h(\theta_q) - R(I_1 + 3T_{r\max}) \leq 0 \quad (\text{eq.3})$$

where:

$R$  = Average radius of the loading surface

$I_1$  = 1<sup>st</sup> invariant of the stress tensor

$T_{r\max}$  = Model parameter which characterizes the maximum tensile strength of the material (the apex of the criteria)

$q_{II}$  = Local deviatoric stress between the current state of stress and the center of the yield surface  $q_{II} = \sqrt{q_{ij}q_{ij}}$  with  $q_{ij} = s_{ij} - I_1 X_{ij}$

$s_{ij}$  = Global deviatoric stress tensor

$X_{ij}$  = Tensor which defines the center of the deviatoric loading surface

$h(\theta_q)$  = Shape factor that allows to take into account the dependency of the behavior with the loading direction

$$h(\theta_q) = (1 - \gamma \cos(3\theta_q))^{\frac{1}{6}} = \left(1 - \sqrt{54}\gamma \frac{\det(q_{ij})}{q_{II}^3}\right)^{\frac{1}{6}}$$

$\theta_q$  = Lode angle

$\gamma$  = Model parameter which quantifies the dissymmetry of the yield surface

### c. Isotropic hardening for CJS-2

The shear loading surface can isotropically expand following the hardening law:

$$\dot{R} = A(R_{fail} - R_{ini}) \exp(-Ap) \dot{p} \quad (\text{eq.4})$$

where:

$\dot{p}$  = increment of hardening variable

$A$  = Model parameter which controls the velocity of the isotropic hardening

$R_{fail}$  = Model parameter which limits the evolution of  $R$

$R_{ini}$  = Initial elastic radius

### 2.2.3 Reference states for CJS-1 and CJS-2

There are two reference states that can make sense for rammed earth: the peak of resistance and the maximum volumetric contraction state. The corresponding surfaces are isotropic surfaces, hold the same shape (together with the shear yield surface) and are written:

$$f^{mvc} = s_{II}^{mvc} h(\theta_s) - R_{mvc} (I_1 + 3T_{rmax}) \leq 0 \quad (\text{eq.5})$$

$$f^{fail} = s_{II}^{fail} h(\theta_s) - R_{fail} (I_1 + 3T_{rmax}) \leq 0 \quad (\text{eq.6})$$

with  $R_{mvc}$  and  $R_{fail}$  the average radii of the maximum volumetric contraction surface and of the failure surface respectively.

### 2.2.4 Volumetric deformations for CJS-1 and CJS-2

Plastic deformations in CJS model associated to the shear mechanism are controlled by the dilatancy law:

$$\dot{\epsilon}_v^{dp} = \beta \left( \frac{s_{II}}{s_{II}^{mvc}} - 1 \right) \frac{|s_{ij} \cdot \dot{\epsilon}_{ij}^{dp}|}{s_{II}} \quad (\text{eq.7})$$

In which:

$\beta$  = dilatancy rate

$s_{II}, s_{II}^{mvc}$  = current state and maximum contraction state, 2<sup>nd</sup> invariants of the stress tensor

$\dot{\mathbf{e}}_{ij}^{dp}$  = the incremental plastic deviatoric strain tensor

The dilatancy law allows contractive or dilative plastic volumetric deformations to be generated according to the position of the stress state with respect to the maximum volumetric contraction state. Here dilatancy is mainly related to a structural increase of volume due to the opening of cracks. When high dilatancy rate is generated the material cannot be considered as a continuum material anymore. The model is then not supposed to retrieve this feature.

### 3. NUMERICAL SIMULATION

#### 3.1 Unconfined compression test

An axisymmetry model of the specimen was used for the simulation. For the sake of simplicity, the model was just composed of 1 grid with an axisymmetry state of stress. The compression is applied as a rigid body motion with a velocity of 0.02  $\mu\text{m/s}$ .

#### 3.2 Identification of model parameters

The basic level of sophistication for the model presented here before and denoted CJS-1, involves 7 parameters. In fact, from the different experiments analysed and due to the less significance of the volumetric deformations in the behavior of the material, we will state that  $R_{mvc} = 0.85 * R_{fail}$ . The elastic properties are defined as the initial tangential properties of the experimental stress-strain curves. The parameters related to the deviatoric plastic mechanism ( $\gamma$  and  $R_{fail}$ ) can be determined directly from compression and tensile actual tests. If the tensile test is not available the usual relationship between the maximum uniaxial compression  $f_c$  resistance and maximum uniaxial tensile resistance  $f_t$  (or  $T_r$  in CJS model) can be used:  $f_t = f_c / 10$ . Finally, the dilative volumetric behavior is controlled by dilatancy rate  $\beta$  which can be derived from the results of the volumetric deformation curves. The set of model parameters for CJS-1 is given in Table 1.

The simulation is extended to the use of CJS-2. For this level of modeling, plasticity is created before reaching failure which allows stresses to be relaxed. It leads to a softer behavior than with CJS-1. This model involved 2 new parameters, the initial elastic radius  $R_{ini}$  of the shear yield surface which gives the extent of the elastic domain and the isotropic hardening parameter  $A$ .  $R_{ini}$  can be identified from a compression test as the zone where a linear behavior is observed and  $A$  is determined by a trial-and-error method. The set of model parameters for CJS-2 is also given in Table 1.

Table 1. Model parameters

| No. | CJS-1        |          | CJS-2        |          | Domain     |
|-----|--------------|----------|--------------|----------|------------|
| 1.  | $G =$        | 2000 MPa | $G =$        | 2000 MPa | Elasticity |
| 2.  | $K =$        | 3333 MPa | $K =$        | 3333 MPa |            |
| 3.  | $\beta =$    | 3.0      | $\beta =$    | 3.0      | Plasticity |
| 4.  | $\gamma =$   | 0.894    | $\gamma =$   | 0.894    |            |
| 5.  | $R_{fail} =$ | 0.27     | $R_{fail} =$ | 0.27     |            |
| 6.  | $T_r =$      | 400 kPa  | $T_r =$      | 400 kPa  |            |
| 7.  | $T_{max} =$  | 1.45 MPa | $T_{max} =$  | 1.45 MPa |            |
| 8.  |              |          | $R_{ini} =$  | 0.05     |            |
| 9.  |              |          | $A =$        | 0.0002   |            |

## 4. RESULTS

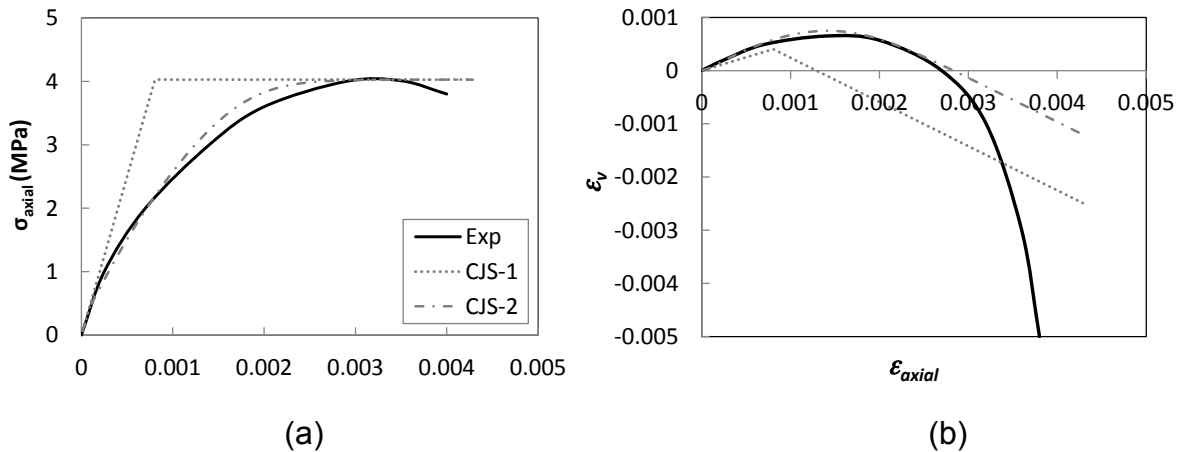


Figure 1. Comparison between experiments and simulations with CJS-1 and CJS-2

The results of the simulated unconfined compression test STR are shown in Figure 1a and Figure 1b. The initial tangent of the stress curve and the peak of response have been retrieved correctly but the behavior is generally too stiff compared to experiments. Figure 1a shows that the use of a simple elastoplastic models (CJS-1) generates an early dilation due to a bad stress path. Then, simulations were performed using CJS-2. In Figure 1a, this second level of the model has been able to capture the nonlinear behavior before reaching failure. The analytical form of the isotropic hardening function which is exponential was suitable to reflect the non linear behavior of rammed earth. The deformation path shows contractive behavior until axial strain 0.15% before the system dilates. However, very sharp dilation cannot be retrieved as in the experiments, but this feature was expected since the actual material cannot be considered as a continuum material anymore.

One must remind that only 7 parameters are required for CJS-1 model: 2 elastic parameters, 4 plastic parameters, and 1 parameter for the description of the volumetric deformations. Then for CJS-2, 9 parameters must be identified. Compared to CJS-1, just one further parameter in CJS-2 ( $A$ ) requires some effort for its identification since it requires a trial-and-error method.

## 5. CONCLUSION

In this paper, an elastoplastic plastic model for studying the behaviour of rammed earth has been presented. The model is validated using a compression test performed on an actual material. The simple elasto plastic model CJS-1 was able to capture some basic features and requires the identification of 7 parameters. The more sophisticated model CJS-2 (9 parameters) was found better to retrieve the non linear behavior of rammed earth. However, further effort is required for the description of the cyclic behavior, a damaged elasticity similar to the case of concrete will have to be implemented in a further level of modeling CJS-3.

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