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Selection, production, and testing of scaled reinforced concrete models and their components

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HIGHLIGHTS

- Assessment of physical scaling approaches for reinforced concrete.
- Theoretical and practical considerations for small-scale models.
- Physical solutions for small-scale reinforced concrete models.
- Example of one-tenth scale, one-gravity soil-structure tests.
- Validations of the one-tenth scale, reinforced concrete models.

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ABSTRACT

This paper presents considerations and procedures for the selection, production, and testing of small-scale, reinforced concrete frames to maintain geometric and kinematic similitude. To verify the proposed solutions, 1/10th scaled models were subjected to adjacent excavation-induced settlements in 1-gravity, soil-structure experiments. Material scaling strategies were verified by comparing the resultant surface soil settlements with published studies and by comparing the model building response with numerical simulation, as well as the extent of the damage with previously established thresholds.

1. Introduction

Full-scale testing is performed to describe real phenomena in engineering. However, due to the relatively high cost and related resources needed to conduct full-scale soil-structure interaction tests, many researchers work at a scale less than full size. The difficulty of such an approach is minimizing (and when possible eliminating) scale effects. When material properties are not properly scaled, elements may not behave in a manner representative of the full-scale problem. These potential negative influences of such arrangements are called scale effects. These scale effects may emerge in terms of geometric, kinematic, and/or dynamic factors. Geometric scaling is relatively well understood and usually satisfied in most experimental work. Yet, kinematic and/or dynamic scaling is less well understood and often ignored, thereby potentially compromising the test results. To fill this gap, the current study describes the material scaling in production, assembling, and testing of reinforced concrete (RC) structural frame models in 1-gravity, soil-structure experiments. The work presented herein was part of a larger study on the effects of adjacent excavations on existing structures [1]. As details of the unreinforced brick masonry scaling have already been published [2], this paper will restrict itself to the RC work.

2. Previous studies and scale model considerations

Experimental results from a small-scale system can be used to predict the response of a full-scale system, if complete similitude is attained. To achieve this, the model should be geometrically, kinematically, and dynamically similar to the full-scale prototype. This can also be expressed as geometrical, material, and process-related similitude [3]. Geometric similitude entails replicating the precise shape of the full-scale model controlled by a single

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scale factor. Kinematic and dynamic similitude require all velocity and force vectors in the model to have the same direction, respectively, as those of the full-scale model, with the corresponding magnitudes related by a single scale factor [4,5]. Dimensional analysis helps satisfy these conditions through the production of dimensionless groups (also called π-sets) composed of dimensional variables for the scale model and the prototype [6]. Matching the dimensionless groups for the scale model and the prototype facilitate the determination of the model parameters. This technique was first proposed by Buckingham (1914) [7] and is often called the "Buckingham pi theorem". The approach was further developed by many others [8–10].

Since its early days, scale models have been used in many disciplines such as hydraulics, structural engineering, naval architecture, and even meteorology and geophysics [11–13]. Scaling in practice, however, often poses problems because while the models (e.g. footings, buildings) are reduced geometrically (e.g. 1/8th scale), unless the material properties (e.g. compressive strength, tensile strength) are re-engineered, they retain the same behavioral characteristics of the full-scale materials [14,15]. Thus, the failure to scale material properties in an experiment can result in non-representative models [6]. However, in practice in scaled structural engineering experiments there is no consistency in adherence to these requirements. In fact, many researchers seem to treat material scaling as an optional activity. For example, while Datin and Prevatt [12] in their one-third scale tests of a three-dimensional (3D), light-framed, wood structure subjected to wind loading applied material scaling by assigning a π-set as Load/(Young's modulus * length^2) to account for the static elastic behavior of the structure, Anil & Altin (2007) [16] working at the same scale to investigate cyclic loading on partially infilled reinforced concrete frames did not incorporate material scaling. Consequently, their overly strong models precluded direct comparisons to the prototype leaving only comparisons between the various scaled models [17]. Similarly, in testing of 3 m high, 2 story models of an RC space frame under harmonic base excitations, De-la-Colina et al. [18] were limited to reporting only qualitative observations. Arguably, exclusion of material scaling could be more critical for RC models than those comprised of a single-material, because problems in RC models can arise from insufficient bond strength between small diameter bars and concrete, excessive aggregate size in the model concrete, or incompatible strength levels in the model [19,20].

Table 1 chronologically presents some recent studies of RC modeling. Material strength similitude in Table 1 describes the application of strength alteration to model materials to capture the prototype behavior. Table 1 implies that material scaling is arguably adopted more often for dynamic loading than static loading and for smaller-scale models starting around a scale of 1/6 [21]. In the studies where material strength similitude was adopted (see Table 1), exclusion of material scaling might have critical effects. Primary amongst them is that heavier loading would have to be applied to fail these overly strong, reduced-size models. This is a widely observed phenomenon in laboratory testing [17]. In this case, excessive loading can cause non-representative stress distributions, alternative failure mechanisms, and unexpected damage patterns. Additionally, under excessive loading, local imperfections within the scale model or local behavior of its structural elements could result in inaccurate structural behavior. Large additional masses may also be needed to increase the inertial forces high enough to cause failure of the structural system, thereby excessively increasing the dead load. In static and pseudo-static, soil-structure interaction experiments the problems is even more critical. Specifically, because a soil's stiffness is proportional with its depth, if full loading is applied to a structural model, there would be a strong likelihood of overloading the soil in its upper regions. This point will be discussed further in the modeling section of this paper.

3. Prototype description

The first step in creating a scaled model is the selection of the prototype. Defining the full-scale structure involves choosing all of the component parts, their physical properties, and the anticipated level and distribution of loading. Since the majority of adjacent excavation-related problems occur in urban areas, a representative edifice was identified as a modern four-story, RC frame structure without infill. To facilitate comparison with the unreinforced masonry structures being tested as part of the larger program, a RC frame was selected of a similar scale. In this arrangement, the floor loads were transferred to the supporting transverse and longitudinal beams in two directions as schematically illustrated in Fig. 1. A "strong-column weak-beam" approach was used where the moment capacity of the column was 1.2 that of the beam. Prototype loads were selected from Table 2 of the Uniform Building Code [31].

A concrete mix having a compressive strength of 34.5 MPa at 28 days was selected in accordance with standard, non-high-rise construction. The prototype concrete's tensile strength was taken as 1/10th of that of the compressive capacity, as a function of the Young's modulus, which was selected as 27,717 MPa based on guidance from the American Concrete Institute [32]. The Poisson's ratio of the concrete was assumed to be 0.15. Deformed bars of grade 60 steel with a modulus of elasticity of 200,000 MPa were selected for the prototype, thereby complying with ACI specifications [32].

The position of the scale models in the testing chamber is shown in Fig. 2. Close-up pictures of the 1/10th scale models and their geometry for the prototype are shown in Fig. 3. The experimental design and procedures for model material selection and construction considerations are explained in the following sections.

4. Experimental scaling considerations

Geometrical, material, and process-related similitude were adhered to closely in this study, despite constrictions in geometrical requirements, material availability, and constructability. Geometric similitude was primary, as it was controlled by the size of the testing chamber, which limited the maximum size to a 1/10th scale for representation of the prototype based on a maximum allowable footprint that avoided boundary condition problems (as established through a Boussinesq analysis).

In a reduced-scale, soil-structure model, confinement stress in the uppermost part of the soil profile is usually minimal. Therefore, the stress applied to soil surface must be restricted to prevent overloading. Consequently, the stress applied to the building materials is, thus, necessarily reduced. For the models to behave as the prototype under this reduced stress, the material capacities in terms of strength and stiffness must also be reduced, as well. This is established formally through the creation of the dimensionless π-sets to determine the specific material properties that need to be altered. Since the strains in structural elements are the function of stresses, as well as of the material stiffness, there needs to be strain parity (Eq. (1)), as previously demonstrated by Tomaževič and Klemenc [33].

$$(\varepsilon)_p = (\varepsilon)_m \tag{1}$$

where $(\varepsilon)_p$ and $(\varepsilon)_m$ are normal strains in the prototype and scale model, respectively (the subscripts *p* and *m* denote the prototype and scale model designations, respectively). By assuming that a