

PSEUDODYNAMIC TESTING OF SCALED MODELS

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ABSTRACT: The pseudodynamic test is increasingly being used for testing structures under seismic loads. Due to the limited capacity of available equipment and also to economic reasons, testing is often required to be carried out on scaled models rather than full-scale structures. Although the similitude laws are well established, the selection of a suitable set of scale factors is often complicated due to the infinite number of possible sets. The various aspects to be considered in selecting a suitable set of scale factors are clarified. The question of possible differences in test results due to a difference in testing procedure is answered by means of tests on identical specimens using three typical procedures. It was found that the results obtained can be considered to be identical for practical purposes.

INTRODUCTION

The current design philosophy, which permits large inelastic response for structures under severe earthquakes with only collapse precluded, has made it imperative to carry out tests using actual earthquake records. The pseudodynamic test is increasingly used for seismic testing of structures in the inelastic range where forces and displacements are large (Takanashi and Nakashima 1986; Mahin et al. 1989). Most often, due to limitations of the testing equipment and the costs involved, the tests are likely to be scaled model tests.

As with any other scaled model test, a large number of means of satisfying similitude are possible, and therefore it becomes difficult to decide as to which would be the most convenient and reliable choice. Previous researchers who carried out pseudodynamic tests (Okada and Seki 1978; Takanashi et al. 1975) have not focused attention on this aspect. In view of this, the present technical note aims to clarify the various aspects to be considered in selecting a suitable set of scale factors. It is shown that the entire range of procedures can be considered to be of two distinct types depending on whether the scale factor is chosen for mass or time. Further, irrespective of the simulation parameters adopted, the procedures may also be classified depending on whether the equation of motion for the prototype or that for the model are used. Results obtained from testing thin-walled cantilever box column specimens show that reliable response histories can be obtained irrespective of the testing procedure adopted.

EXPERIMENTAL PROCEDURES

For a typical problem involving time-dependent loading, since there are three fundamental dimensions, namely, mass M , length L , and time T , three independent scale factors may be selected for true modeling (American 1970). The other scale factors can then be derived according to the principles of dimensional analysis.

In particular, the pseudodynamic test is carried out in a series of steps. In each step, the computed displacement, x_p , is quasi-statically imposed on the specimen, and the restoring force, R , developed is measured. This value of R is then used

to compute the displacement to be applied in the next step, x_{p+1} . In the case of a scaled model test, using the suffix "p" to denote the quantities related to the prototype and "m" to denote the quantities related to the model, it can be said that displacement x_m is applied and restoring force R_m is measured. The aim is to obtain x_p , the response of the prototype. Thus, only forces and displacements are applied and measured, and the test itself is carried out in pseudo time. Therefore, the principal aim of testing scaled models is to achieve a reduction in size (length) of the test specimen to suit the available test equipment and to reduce the load (force) to a level below the maximum capacity of the actuators. This will automatically reduce the cost of the test. Thus, the only scale factors of interest are those for length and force. The scale factors for the other quantities (time and mass) are of less concern since these are used only in the numerical calculations. Assuming that the model is made of the same material as the prototype and imposing the condition that the scale factor for force be S^2 , where S = scale factor for length, preserving the stress identity leaves only two possible choices. These two choices correspond to the selection of a convenient scale factor for mass or time, respectively. Each choice will now be examined in more detail.

PROCEDURE 1

In this procedure the scale factor for mass is chosen. When the distribution of gravity loads plays an important role, it is convenient to select the scale factor for mass as S^3 . This, coupled with the condition that the scale factor for force should be S^2 as mentioned previously, yields the scale factor for time as S . Such a scaling down of time would have complicated the testing if a conventional dynamic testing method like the shaking table test is used, due to the limitation on the shaking speed. However it poses no problem in pseudodynamic testing since the test is carried out in pseudo time. The scale factors for the other quantities can be readily derived based on dimensional analysis and are shown in Table 1.

At this stage, it may also be noted that depending on the equation solved in the computer, two distinct procedures are possible for any set of scale factors. If the equation of motion for the prototype is solved, the procedure will be identified by the letter A. Thus, procedure 1A will imply that the scale factor for mass is chosen and the equation of motion for the prototype is solved. The equation of motion can be written as

$$M_p \ddot{x}_p + C_p \dot{x}_p + R_p = -M_p \ddot{x}_{0p} \quad (1)$$

where M_p = mass; C_p = damping coefficient = $2\xi\sqrt{K_p M_p}$; ξ = viscous damping ratio; K_p = elastic stiffness, R_p = restoring force; and \ddot{x}_{0p} = ground acceleration. The preceding equation is solved to obtain x_p , which is then scaled down to get x_m applied to the model. Corresponding restoring force R_m is measured and scaled up by S^2 to get R_p , which is again used to

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TABLE 1. Scale Factors Used in Pseudodynamic Test Procedures

Quantity (1)	Dimensions (2)	Procedure 1 (3)	Procedure 2 (4)
Length	L	(S)	(S)
Mass	M	(S^3)	S
Time	T	S	(1)
Stress	$ML^{-1}T^{-2}$	1	1
Velocity	LT^{-1}	1	S
Acceleration	LT^{-2}	$1/S$	S
Force	MLT^{-2}	(S^2)	(S^2)
Stiffness	MT^{-2}	S	S
Damping ($C = 2\xi\sqrt{KM}$)	MT^{-1}	S^2	S
Natural frequency ω	T^{-1}	$1/S$	1

Note: Scale factor for quantity i ; $S_i = i_p/i_m$; items in parentheses indicate specified factors.

solve the equation of motion. Thus, the response of the prototype is obtained directly during the test.

If the equation of motion for the model is solved, the procedure will be identified by the letter B. The equation is given by

$$M_m \ddot{x}_m + C \dot{x}_m + R_m = -M_m \ddot{x}_{0m} \quad (2)$$

Thus, the test is carried out entirely on the model without considering the prototype. However, this requires that the accelerogram be modified accordingly. For procedure 1B this can be achieved by increasing the amplitude and dividing the time by scale factor S , for use in the calculations.

PROCEDURE 2

When the gravity loads do not play an important role, the scale factor for time can be chosen. Although any scale factor can be used, the simplest would be to use a scale factor of unity. The scale factor for mass is then equal to S , so as to give a scale factor for force equal to S^2 . The scale factors for the other quantities are shown in Table 1. It may be noted from this table that when using the equation of motion for the model (procedure 2A), the amplitude of the accelerogram has to be scaled down by S . The means of carrying out the test is then similar to that described in procedure 1.

An interesting variation of this procedure has been widely used in Japan and needs to be clarified. In this variation the similitude relations are the same as described previously, but the earthquake accelerogram is used without scaling down the amplitude. The procedure has been justified by stating that since the frequency effects are preserved, qualitative information can be obtained regarding the seismic performance of the structure subjected to the given earthquake. This is possible in the elastic range. However, in the inelastic range it should be realized that since the forces are no longer proportional to the displacement, the exact response of the structure subjected to the original record cannot be obtained. The deviation will increase as S becomes larger than unity. Also, since the procedure is equivalent to using an accelerogram of amplitude S times larger than the prescribed one, care should be taken, especially for higher values of S , to ensure that the specimen does not fail prematurely due to the high magnitude of the earthquake. In the present study, since the value of S was 8, it was realized that the procedure cannot be used for testing due to this reason.

VERIFICATION TESTS

To verify possible differences in test results and convenience in testing, tests were carried out using the three procedures: 1A, 1B, and 2A. Identical specimens modeling thin-

walled steel bridge piers of hollow box section with a scale factor "S" equal to 8 were used. Such piers exhibit inelastic behavior due to the inception of local buckling under the combined action of the dead load of the superstructure and the cyclic lateral loads due to the earthquake (Usami and Kumar 1996). The dead load of the pier itself is a small fraction of the dead load of the superstructure, and is unimportant. The latter is simulated by applying a constant axial load to the model by means of a hydraulic jack. The ratio of axial load to the squash load was taken to be the same in both the model and the prototype ($P_m/P_{ym} = P_p/P_{yp}$), so as to make the P - δ effect coincide in both cases. The earthquake accelerograms used are those for level 2 prescribed by Public (1993), for an ultimate ductility check.

The entire bridge pier-superstructure system was idealized as a single-degree-of-freedom system, and the corresponding equation of motion was solved using an explicit integration method (Mahin et al. 1989). The mass of the system was specified and the viscous damping ratio ξ was taken as 0.05—the value prescribed for general seismic design (Public 1993). Although the value seems to be a little high for steel structures, it should be realized that in the inelastic range, hysteretic damping plays a more important role than viscous damping. Ground acceleration \ddot{x}_0 was specified in the form of a digitized record.

The cyclic lateral load arising from the earthquake was applied by means of an MTS servocontrolled hydraulic actuator (capacity 343 kN, maximum stroke ± 125 mm). The displacement at the free end was measured by a linear displacement transducer with a maximum range of 150 mm. Additional details of the test setup can be found in Usami and Kumar (1996).

TEST RESULTS

The results of tests carried out using procedures 1A and 2A are compared in Fig. 1. The accelerogram used was that for medium-stiff ground (Ground Type II). The forces and displacements are for the specimen, and the time corresponds to that of the prototype. In this figure, procedure 1A gives a slightly higher maximum displacement than procedure 2A, which fi-

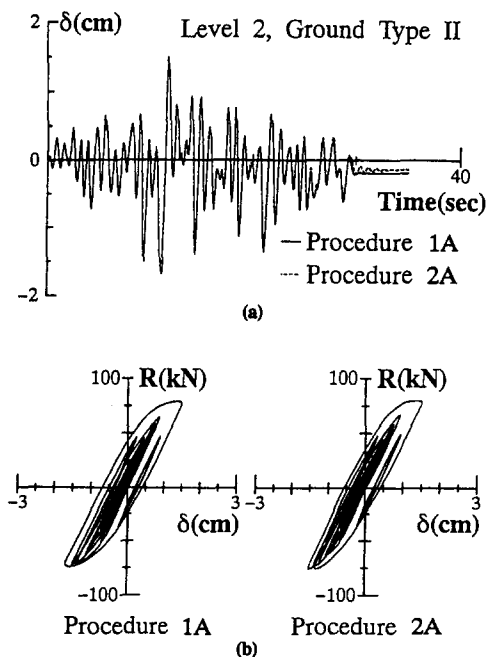


FIG. 1. Comparison of Results Obtained by Procedures 1A and 2A: (a) Time Histories of Displacement; (b) Hysteretic Loops

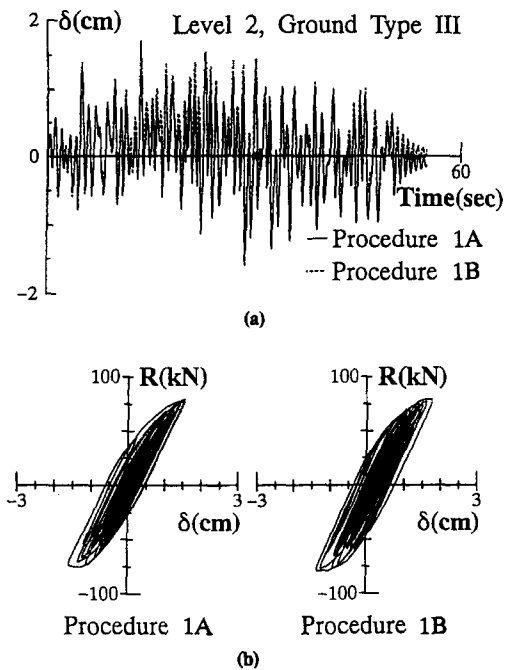


FIG. 2. Comparison of Results Obtained by Procedures 1A and 1B: (a) Time Histories of Displacement; (b) Hysteretic Loops

nally results in a slightly larger residual displacement. Although it is difficult to determine the source of this discrepancy, it may be presumed that it is due to slight differences in the specimen characteristics (welding, etc.) rather than the use of a particular procedure. Since the magnitude of the forces applied and displacements measured are the same in both tests, the accuracy of the equipment used will also be the same in both cases. On the whole, the discrepancy is small enough to conclude that the results obtained are the same for practical purposes.

With regard to the manner of carrying out the tests, the results obtained using procedures 1A and 1B were also found to be the same, keeping in mind the preceding factors mentioned.

These are shown in Fig. 2 for tests carried out using the accelerometer for soft ground (Ground Type III). Thus, it can be concluded that as long as the scale factors for length and force are the same, the test results obtained with different procedures are not likely to be affected by the precision of the testing apparatus.

CONCLUSIONS

The various aspects to be considered in selecting a suitable set of scale factors for pseudodynamic tests were clarified, and the possible similitude relations were classified into two types. Such a classification helps to select the most suitable procedure and similitude relationships for pseudodynamic testing using available equipment. Pilot tests using three typical procedures show that as long as the scale factors for length and force are the same, the results obtained using each procedure are practically coincident.

APPENDIX. REFERENCES

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