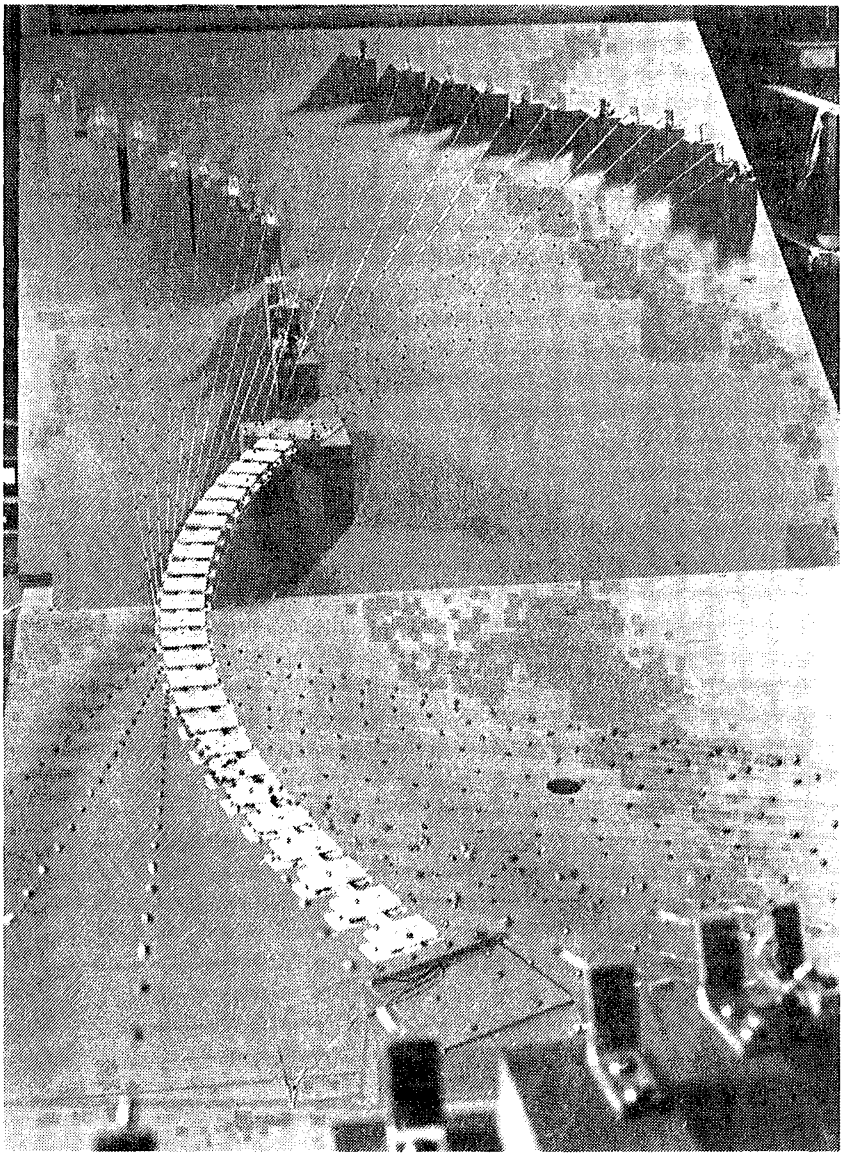

Plate 3 1/200 Scale Model

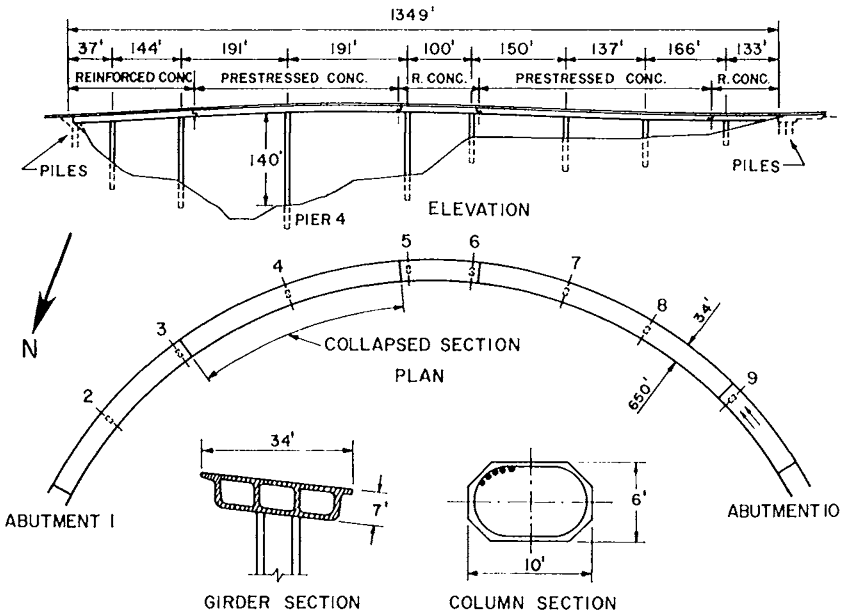

Fig. 1 Structural system of the South Connector Overcrossing

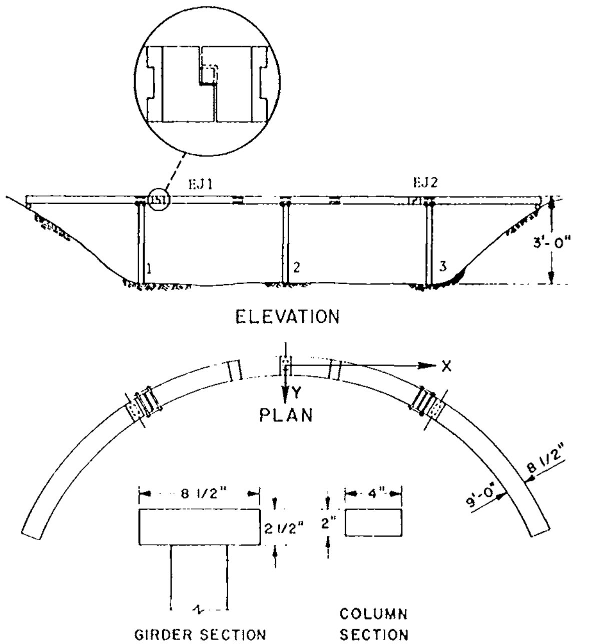

Fig. 2 Schematic of test model

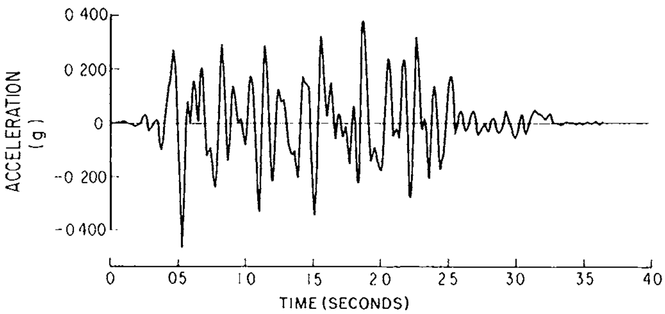

Fig. 3 Transverse support acceleration

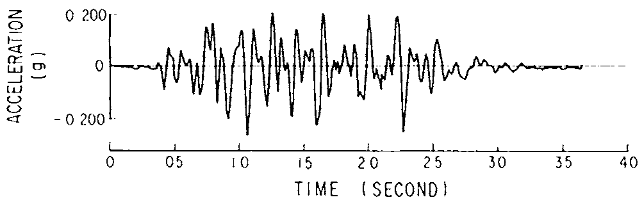

Fig. 4 Vertical support acceleration

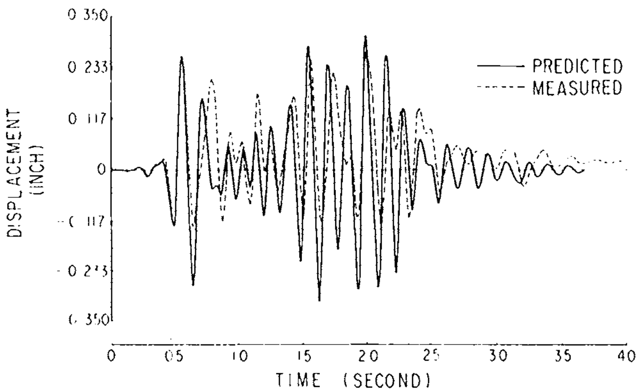

Fig. 5 Transverse deck displacement at location of center column - Linear Model

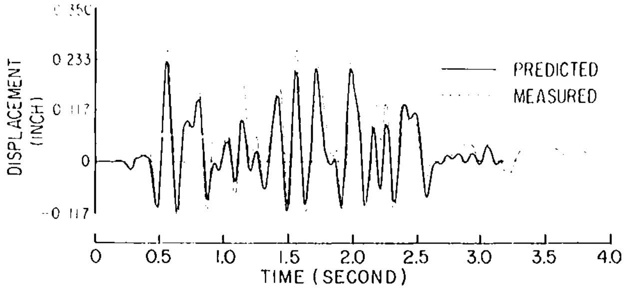

Fig. 6 Transverse deck displacement at location of center column - Nonlinear Model

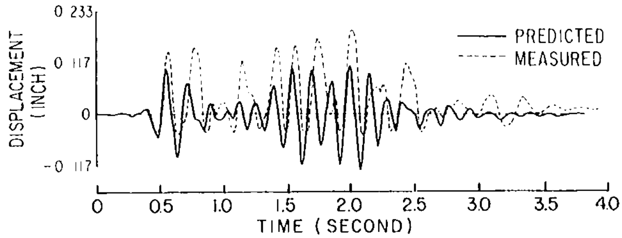

Fig. 7 Expansion joint separation - Linear Model

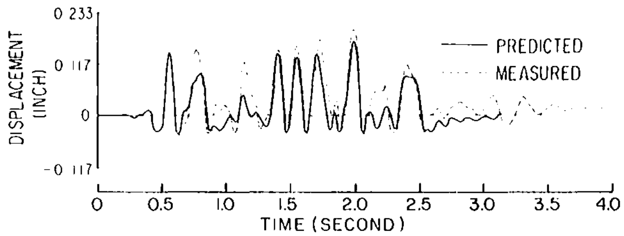

Fig. 8 Expansion joint separation - Nonlinear Model

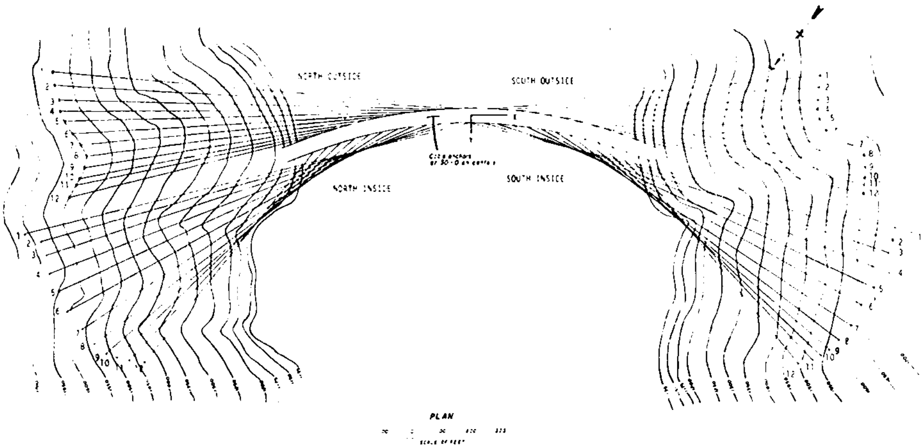

Fig. 9 Layout of Prototype Bridge (1 ft = 0.305 m)

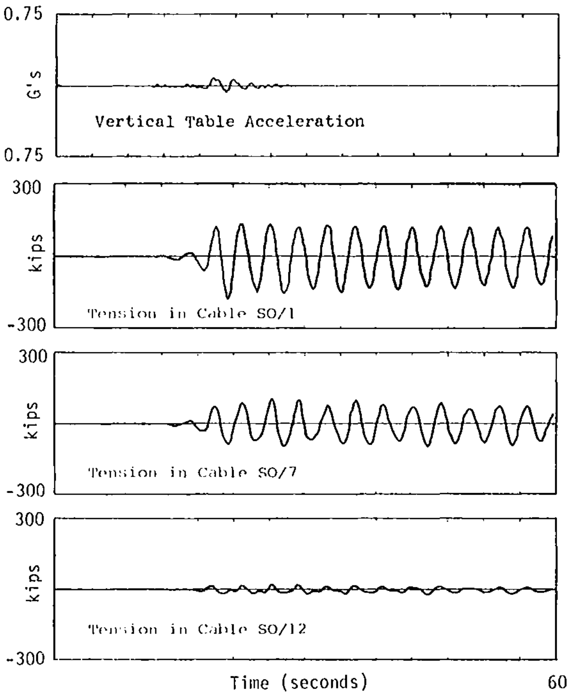

Figure 10 Response to Vertical Table Motion

SP 73-7

Scale Modeling of Buried Reinforced Concrete Structures Under Air-Blast Loading

By James K. Gran, John R. Bruce,
and James D. Colton

Two 1/30-scale models of reinforced concrete cylindrical missile shelters were built and tested to study the response of buried reinforced concrete structures subjected to severe dynamic loads. To assess the applicability of small-scale modeling to this type of problem, the results of the 1/30-scale model tests were compared with 1/6-scale results from a parallel program.

A comparison of the 1/30-scale and 1/6-scale tests shows that the surface loads and soil responses matched and that the structural responses agreed very well. For the elastic structures, concrete surface strains measured in the 1/30-scale test and reinforcing steel strains measured in the 1/6-scale test showed that the direct loading wave, the reflections from the base and the closure, the base and closure flexure, interface friction, and soil resistance to punchdown were all reproduced accurately at 1/30-scale.

For the inelastic structures, the responses agreed up to the time of failure of the 1/6-scale structure. Failure in the 1/6-scale structure occurred at an apparently locally weak section of concrete. Concrete surface strains measured in the 1/30-scale test and reinforcing steel strains measured in the 1/6-scale test showed excellent agreement above the failure location. The 1/30-scale strains throughout the structure were also in excellent agreement with the predictions of numerical analyses.

Keywords: blast loads; blast resistant structures; dynamic loads; dynamic response; dynamic tests; failure; models; reinforced concrete; scale (ratio); strains; subsurface structures.

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INTRODUCTION

The purpose of the research described in this paper was to assess the applicability of using geometric scaling at very small scale to study the response of buried reinforced concrete structures subjected to air blast loading. The approach was to build and test two 1/30-scale models of reinforced concrete missile silo structures [1] and compare the responses with those from 1/6-scale tests conducted by the Civil Engineering Research Facility at the University of New Mexico [2]. The best modeling techniques currently available were used to allow identification of areas requiring additional research or technique improvement to enhance the reliability of small-scale modeling.

The structures of interest exhibit several response features. The direct load from the air blast produces an axial compression stress wave that propagates down the length of the structure. The blast wave propagates more slowly through the soil, producing radial compression and vertical shear on the outside of the structure. The wave in the structure may be elastic or inelastic, and may produce failure. When it reaches the base of the structure, the wave reflects, the base responds in bending and shear, and the soil beneath the base arches. Again, this may also result in structural failure.

STRUCTURAL DESIGNS AND FABRICATION

Two structures were built and tested: a 'B' structure designed to respond elastically, and an 'A' structure designed to respond inelastically. Both designs consited of a long, cylindrical tube with a thick cover plate and base plate. In 1/30-scale their overall length was 1.28 m, and the inside diameter was 142 mm. The wall thickness of the 'B' structure was 20 mm; for the 'A' structure it was 10 mm. The concrete strength in the 'B' structure was 40 MPa; in the 'A' structure it was 24 MPa. The main reinforcement for both structures was 1% steel in the longitudinal and circumferential directions, placed in two layers. The main reinforcement was made of 4130 steel welding wire that was deformed and heat-treated to produce the desired bond and strength properties. For the 'B' structure 1.14-mm-diameter wire was used; for the 'A' structure 0.89-mm-diameter wire was used. The yield strength of the wires was 590 MPa. Radial stirrups at each of the approximately 4000 bar intersections provided shear reinforcement.

Deforming the wires was accomplished by using a mechanism consisting of two knurling wheel pairs, whose teeth indent the wire as it is pulled between the wheels. The depth of the identation, controlled by the wheel spacing, was 0.05 mm for the 1.14-mm-diameter wire and 0.03 mm for the 0.89-mm-diameter wires. A close-up photograph of the deformed wires is shown in Fig. 1(a). Direct pullout tests were conducted with the deformed wires embedded in 35-mm-diameter microconcrete cylinders. The results are shown in Fig. 1(b) where they are compared with 1/6-scale test results and prototype bond data.

For the heat treatment, the wires were tied in 10-mm-diameter bundles and placed in a stainless steel basket for handling. The first step was to heat the wires in a controlled environment to 870°C and then to oil-quench them. The second step was to temper the wires at 660°C to 730°C for 1 hour. This process was calibrated first using small sample batches. The yield strength as a function of tempering temperature and batch size is shown in Fig. 1(c). Tensile tests showed that uniform strength was achieved along the length of the 1.5-m-long wires. Strength varied less than 5% from wire to wire. A typical stress-strain record is shown in Fig. 1(d), where it is compared with 1/6-scale data.

Different techniques were used for the other reinforcement. The radial stirrups were 0.51-mm-diameter, undeformed, 1020 steel wire, which was partially annealed at 540°C for 1 hour to produce a strength of 480 MPa. The cover plate and base plate reinforcement was 2.67-mm-diameter mild steel wire, which was cold-worked during the deformation process to produce a strength of 335 MPa.

The microconcrete used in both structures consisted of a mix of graded sand, water, and Type III Portland cement, with no admixtures. The sand was half Monterey No. 20 and half Monterey No. 30. The aggregate diameter ranged from about 0.4 mm to about 1.3 mm. For the 'B' structure the mix proportions (by weight) were 3.61 parts sand, 0.67 parts water, and 1.00 part cement, and the microconcrete was cured in water at 38°C for 7 days. For the 'A' structure the mix proportions were 3.75 parts sand, 0.72 parts water, and 1.00 part cement, and the microconcrete was cured in air at 25°C. Both structures were tested about 4 weeks after they were poured.

The microconcrete was poured in lifts measuring 200 mm high for the 'B' structure and 100 mm high for the 'A' structure. Plexiglas rings were used for the outer forms, and urethane foam cores were used for the inner forms. The assembly was mounted on a vibration table and vibrated 2 to 5 min for each lift. Sample cylinders measuring 20 mm in diameter by 100 mm long were cast with each lift and attached to the structure mold so that they would experience the same vibration as the structure. Measurements showed that in both structures, the walls were held to within 10% of the design thickness, except at the base where 15% variations were measured.

Test specimens 40 mm in length were cut from the central portion of the sample cylinders. The test specimens were then capped with Hydrostone, instrumented with strain gages, and tested in an Instron testing machine. The strength of the 18 specimens from the 'B' structure averaged 39.1 MPa with a standard deviation of 3.1 MPa. The strength of the 32 specimens from the 'A' structure averaged 23.0 MPa with a standard deviation of 2.7 MPa. In neither case was any trend apparent in the strength variation along the length of the structures. Typical compression stress-strain records are shown in Fig. 2, where they can be compared with records from the 1/6-scale and prototype concretes of similar strengths.

LOADING AND INSTRUMENTATION

The 1/30-scale experiments were conducted in a rigid facility similar to the one used for the 1/6-scale tests. The configurations for the 1/30-scale tests are shown in Fig. 3. Concrete sand (ASTM C33) was used for the backfilled soil at both scales. It was rained into place from a height exceeding 0.75 m to achieve a uniform density of about 1750 kg/m^3. The explosive charge design was scaled from the 1/6-scale charge; it consisted of four layers of Primacord explosive and polystyrene foam, covered by a 0.44-m-deep layer of sand.

Several types of instrumentation were used to record the loads and the structural response. The gage locations are shown in Fig. 3. Blast pressure on the surface of the soil was measured using piezoelectric pressure gages mounted in cases, with debris shields similar in design to those developed at the U.S. Air Force Weapons Laboratory. Soil acceleration was measured with piezoelectric accelerometers mounted in hollow plastic cases whose gross density matched that of the sand. Soil stress was measured using a diaphragm gage designed by the U.S. Army Corps of Engineers. Concrete strain was measured with 12-mm-long, Mylar-backed gages, bonded to the concrete with epoxy and shielded with copper foil. Structure acceleration and interface pressure were measured with piezoelectric gages whose mounts were cast in the microconcrete. All the gage signals were conditioned and recorded in analog form, then digitized electronically at a sampling rate of 6 microsecond/point.

In the gage records discussed below, the gage locations are given in terms of the ratio of the gage depth to the overall length of the structure (d/L). For the purpose of comparison, all the data from the 1/6-scale test were digitized manually and scaled to correspond to the 1/30-scale records [6].

RESULTS AND COMPARISONS

Elastic 'B' Structure

A comparison of the results from the 1/30-scale and 1/6-scale tests of the 'B' structure shows that the surface loads and soil responses were matched, and that the structural responses agreed very well. The direct loading wave, the reflection from the base, the base response, and the soil shear loading were all reproduced accurately at 1/30-scale.

Blast pressure and soil stress records from the 'B' structure tests are compared in Fig. 4. This comparison shows that the loads on the structure were well matched. The major difference was that the soil wave speed in the 1/6-scale test (400 m/s) was higher than that in the 1/30-scale test (250 to 400 m/s). This is thought to be due to differences in soil density,resulting from imperfect soil placement. The measured peak soil stresses agreed well with those calculated from the independently measured soil density, wave speed, and soil velocity (time integrals of acceleration, not shown).

Concrete surface strains measured in the 1/30-scale test and reinforcing steel strains measured in the 1/6-scale test are compared in Fig. 5. The precursor in the 1/30-scale records is the result of electrical noise generated from the detonation of the explosive. This noise had a peak amplitude equivalent to approximately 250 microstrain and a frequency of about 4000 Hz. The amplitude decayed with time, but was not negligible during the first 500 microseconds of the test. This makes the interpretation of the records more difficult; however, the principal loading effects can be identified.

When the direct blast load wave in the structure arrived at a particular location, the axial strain rose sharply in compression. The tensile reflection of this wave from the base then reduced the axial strain sharply. Between 0.5 millisecond and 1.0 millisecond later, depending on the location, the strain again rose due to the soil/structure interaction shear load. Not shown are the circumferential strains, which were first tensile due to the axial compression, but then abruptly changed to compression when the soil wave arrived. The comparison with the 1/6-scale records indicates that all the features of the response were reproduced in the 1/30-scale test, although the magnitude of the strains differed somewhat.

The records showing the base response are compared in Fig. 6. Oscillations in the base acceleration and velocity indicate that