IN SITU EXPLOSION TESTS TO DETERMINE THE SEISMIC BEHAVIOUR OF AN UNDERGROUND LARGE-SIZE PIPE FOR WATER SUPPLY

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SUMMARY

Calibrated blast vibrations have been used in order to simulate the seismic excitation of an underground large-size pipe for water supply made of fiberglass reinforced resin.

The criteria adopted for correlating the blast excitation with the seismic one, based on a comparison of the frequency ranges involved, response spectrum shapes, vibration intensities and durations are discussed. Moreover, the paper describes the operating procedures and the measuring instruments used to determine the characteristics of both excitation and response of the pipe. Finally, some comments on the results obtained are set forth.

INTRODUCTION

In order to check the seismic resistance of a large-sized underground pipe made of fiberglass reinforced resin, to be used for water supply in the areas of Western Sicily hit by the earthquake of 1968, an extensive research has been carried out on a full scale specimen (inner diameter 220 cm, thickness 1,8 cm, length 24 m).

Owing to the large amount of energy required for the excitation of the pipe, the use of calibrated and controlled explosions has been considered the only appropriate and practical for reaching the acceleration levels expected for large intensity earthquakes. Moreover, tests on a full scale specimen have been preferred to model studies owing to the difficulties of reproducing satisfactorily, in a smaller scale, both pipe material characteristics and soil conditions.

Tests were carried out both without and with water in the pipe (free head and pressurized at 6 bars) reproducing unfavourable seismic conditions, that - according to Japanese observations - occur when the pipe is buried

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with shallow head in a soft soil (Ref. 1). Actually the pipe has been buried in a clayey-silty soil; the depth of the trench was equal to the diameter of the pipe, which was covered with a soil layer having a trapezoidal cross section as high as the pipe radius.

Special care has been devoted to the design and installation of the pipe end restraints, in order to reduce their influence on the static and dynamic behaviour of the pipe itself.

Soil and pipe behaviour has been measured by the following set of instruments:

- 4 triaxial accelerometers buried into holes, placed along lines connecting the explosion sites to the pipe;
- 24 two-component strain rosettes placed on the inner and outer surface of the pipe at three sections, to measure local strains in correspondence of vertical and horizontal diamters;
- 6 proximity transducers mounted on proper devices inside the pipe, to measure changes in diameter length in horizontal and vertical directions, at three different sections;
- 15 accelerometers placed along the horizontal diameter of the pipe and on the end restraints;
- 12 pressure cells to measure pressure variations between soil and pipe in three sections in correspondence of vertical and horizontal diameters.

Fig. 1 schematically shows the pipe conditions and the positions of the measuring instruments. The data acquisition and processing equipment was based on an analog to digital "sample and hold" converter and on a minicomputer for data storage and processing.

CRITERIA FOR EARTHQUAKE SIMULATION

The difficulties of obtaining by means of explosions a complete reproduction of the seismic motion are well known, the most significant differences being a higher energy content at higher frequencies and a shorter duration of the blast generated earthquake with respect to the actual earthquakes. It follows that a comparison between the two types of phenomena cannot be based simply on the comparison of the maximum acceleration values, but has to be made by comparing the relevant response spectra in a suitable frequency range.

In the present case the following procedure has been adopted:

Choice of the "shape" of the reference spectrum

Since no information was available about the spectral characteristics of the earthquakes of the area, the Newmark spectrum for nuclear plants (Ref. 2) has been adopted as reference spectrum. Let $S(\infty) = a_{max}$ indicate the maximum ground acceleration, and $\alpha_N(f, \nu)$ the "shape" of the normalized spectrum (the normalization criterion being $\alpha_N(\infty, \nu) = 1$); it results:

$$S_{Ref.} = S(\infty) \cdot {}_N(f,\nu)$$

where f is the frequency and ν the damping coefficient.

For the present case, the value $\nu = 10\%$ has been assumed.

Choice of the frequency range of interest

As already mentioned, it is not possible to obtain a satisfactory reproduction of the reference spectrum over the whole seismic frequency range. Consequently, the criterion has been chosen of determining, by means of a preliminary research, the most dangerous frequency range for the pipe in the testing conditions, and of reproducing the seismic spectrum in that range. Therefore, forced vibration tests have been performed, with the aim of determining the amplification frequencies of the system formed by the pipe and the nearby soil. These tests have been carried out by means of a forced vibration generator (vibrodyne) delivering variable frequency sinusoidal forced in vertical direction as well as in horizontal direction perpendicular to the pipe axis. The vibrodyne, capable of delivering a force up to 10 tons, has been mounted on a concrete block weighing approx. 12 tons, partially buried into soil close to the pipe midspan.

By means of these tests the transfer functions between the system response and the exciting force have been determined. No amplifications have been found at frequencies lower than 9,7 Hz approx.; this justified to limit the frequency range to be examined from approx. $f_1 = 8$ to $f_2 = 25$ Hz, the latter being usually considered as the upper limit of the seismic frequency range.

Duration of vibrations

Generally speaking, the time history of an earthquake shows three phases: an initial build-up, a period of high amplitude vibrations, the final decay. The duration of the central phase varies in a very wide range according to geology, fault mechanisms, distance from epicenter etc., from less than 1 sec up to approx. 30 sec (Refs. 3, 4). For the present case, it has been deemed adequate to adopt a short duration of the central phase, considering the characteristics of the Italian earthquakes. This choice has also allowed to reduce the high costs of the tests.

Comparison between blast vibrations and reference earthquake

Based on the above considerations, the following conservative criterion for the comparison between the artificial and the reference quake has been adopted:

$$S_b(f,\nu) \geq S_{Ref.}(f,\nu)$$

in the frequency range $8 \text{ Hz} \leq f \leq 25$ Hz.

Therefore, for a given artificial earthquake, the spectrum of which be $\overline{S}_b(f,\nu)$, the above criterion allows a reference spectrum $S_{Ref.}(f,\nu)$ to be determined, and consequently an "equivalent" value $\overline{S}(\infty)$ of the maximum acceleration.

As already mentioned, the actual maximum values of the blast vibrations are much larger than $\overline{S}(\infty)$.

EXPERIMENTAL PROCEDURE FOR BLAST EXCITATION

Preliminary blast tests

In order to establish the most suitable testing technique for the simulation of the earthquake characteristics according to criteria discussed above, 15 preliminary tests (with reduced charge quantities) have been carried out. During these tests the following parameters have been made to vary:

- distance R from the shot and the pipe
- number N and array of charges
- quantity Q of individual charge
- microdelays ΔT among the explosion of the individual charges.

Their effects on the energy distribution at different frequencies, duration of vibrations, and attenuation have been examined. Fig. 2 shows the array of the charges used for both preliminary and earthquake tests.

From preliminary tests the following main information were obtained:

- energy content of blast vibrations lies mainly in the high frequency range; however the "predominant" frequencies lower as the distance R between shot and measuring point increases;
- at constant R values, number of charges and micro-delays do not influence the frequency content;
- duration of vibration (very short for a single shot) increases as N and ΔT increase. Durations of at least 1-2 sec are reached when N = 3-4 and ΔT = 250-350 msec;
- values of the response spectrum $S_b(f,\nu)$ adequate for simulation of a reference earthquake with a maximum ground acceleration of at least 0,1 g can be obtained when the "reduced distance" D (defined as $D = R \cdot Q^{-1/2}$) ranges from 6 to 7.

Earthquake type blast tests

Based on the results of the preliminary tests, the values of the blast characteristics for earthquake tests of the pipe were chosen as follows:

N = 3-4; ΔT = 250-350 msec; R = 60-100 m; D = 6-7 m/kg$^{1/2}$; Q = 75-275 kg

As already mentioned, it has been considered advisable to limit the number of N, and consequently the duration of the phenomenon, for economical reasons; however, a longer persistence could have been obtained by increasing the number N of individual charges. Seven tests have been performed using different combinations of the values of the parameters listed above, with the aim of checking the earthquake resistance of the pipe.

Two tests have been performed with direction of excitation parallel to that of the pipe axis; the remaining 5 tests with direction perpendicular to the previous one. Some characteristics of the explosions are listed in table A.

TEST RESULTS

The main results of the tests carried out are summarized in table A; as it can be seen, the peak accelerations (unfiltered) reached very high values (approx. 0,75 g in test 3).

Examples of the time histories of soil recorded at a distance of 5 meters from the pipe are given in Fig. 3, together with some response time histories of the pipe. These oscillograms show that the vibrations of the pipe lasted longer than those of the soil.

A ground response spectrum (relevant to test no. 3) is given in Fig. 4, and is there compared with the reference Newmark spectrum.

At the end of each blast test, residual values for both strains and displacements were measured at different points of the pipe, thus indicating that permanent settlements of the pipe-soil system were produced by the explosions. This confirms that the intensity of the vibrations reached rather large and significant values, notwithstanding the short duration of the phenomenon; nevertheless, no damage to the pipe nor to its restraints has been noticed.

CONCLUSIONS

The blast tests carried out can be considered a significant check of the seismic resistance of the pipe, since the intensity of the vibration produced in the soil and recorded on the pipe can be compared to that of a strong motion earthquake. It follows that blast induced vibrations can be used successfully for simulation of earthquake effects, for engineering purposes, provided the response of the structure under test be stiff enough not to show natural frequencies lower than approx. 5-6 Hz. The duration of the event can be extended by using a larger number of microdelayed shots: acceptable figures could be approx. 10 shots with a delay of 250-350 msec.

However, the problem of reproduction of earthquake spectra with significant energy content in a frequency range lower than that mentioned above (as could be necessary for tests of flexible structures) is still open, since the use of very large charges (to obtain high intensity) at very large distances (to reduce frequency) is obviously not practical. A possible technique to solve this problem could be the use of reflecting devices suitably placed into the soil (Ref. 5), the effect of which is that of concentrating the blast energy towards the structure, and of increasing the duration of the vibrations. Theoretical studies as well as experimental tests on models and in situ, sponsored by ENEL and ENEA, are in progress.

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Table A: CHARACTERISTICS OF BLAST TESTS AND MAIN RESULTS OBTAINED

Test number	Excitation direction (1)	Pipe conditions	Number of charges N	Individual charge Q (Kg)	Microdelays ΔT (msec)	Response of soil (2)				Maximum response of pipe (3)			
						Horizontal direction		Vertical direction		Strain	Displacem.	Peak accel.	Soil/pipe pressure
						Intensity (cm/sec^2)	Duration (msec)	Intensity (cm/sec^2)	Duration (msec)	(10^{-6})	(mm)	(cm sec^{-2})	(Kg/cm^2) (4)
1	P	50%	4	75 + 3 · 100	300	115	800	155	850	58	0,5	247	0,07
2	P	full	3	3 · 100	350	130	700	150	700	83	1,9	346	0,17
3	T	50%	3	3 · 100	350	290	500	350	250	176	2,0	752	0,08
4	T	50%	4	4 · 100	250	155	1100	195	900	67	1,1	257	0,08
5	T	full	3	3 · 100	350	305	500	360	300	87	1,5	467	0,14
6	T	full	3	3 · 100	350	170	800	120	800	148	0,7	241	0,07
7	T	full	4	2·200; 350; 400	200,200 350	150	950	175	600	79	1,0	405	0,09

NOTES: (1) P, T = parallel and transversal to the axis of the pipe.
(2) Records made at 5 m from the axis of the pipe, midspan position.
(3) Referred values have been measured at different points. Not all the measuring points were recorded during tests.
(4) All the maximum values have been attained at midspan, lower end of vertical diameter.

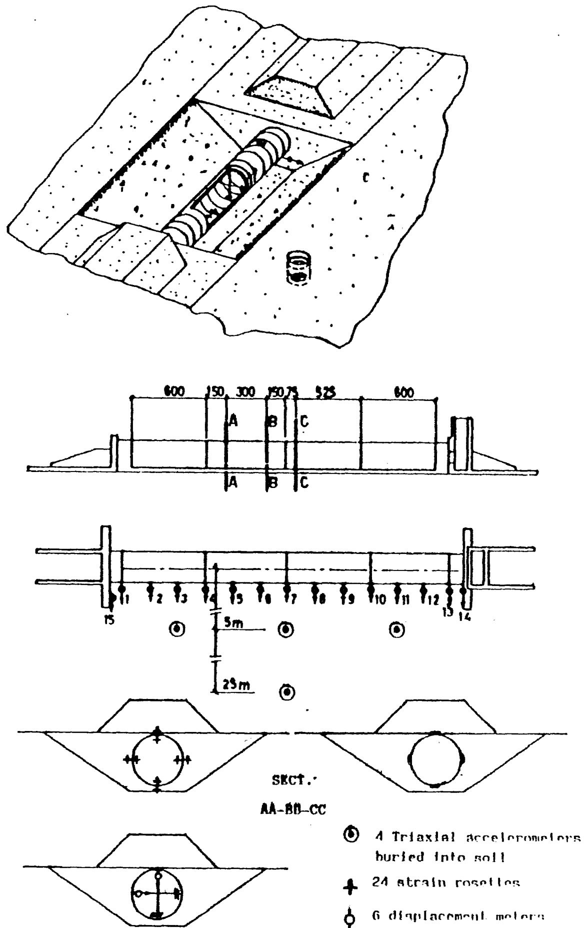

Fig. 1 : Pipe conditions and positions of measuring instruments

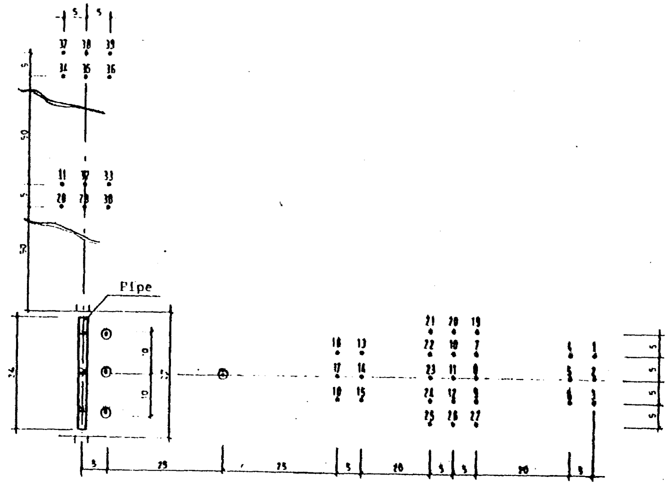

Fig. 2: Array of the charges for prelimiminary and earthquake tests

• charge positions ⊙ triaxial accelerometers in soil

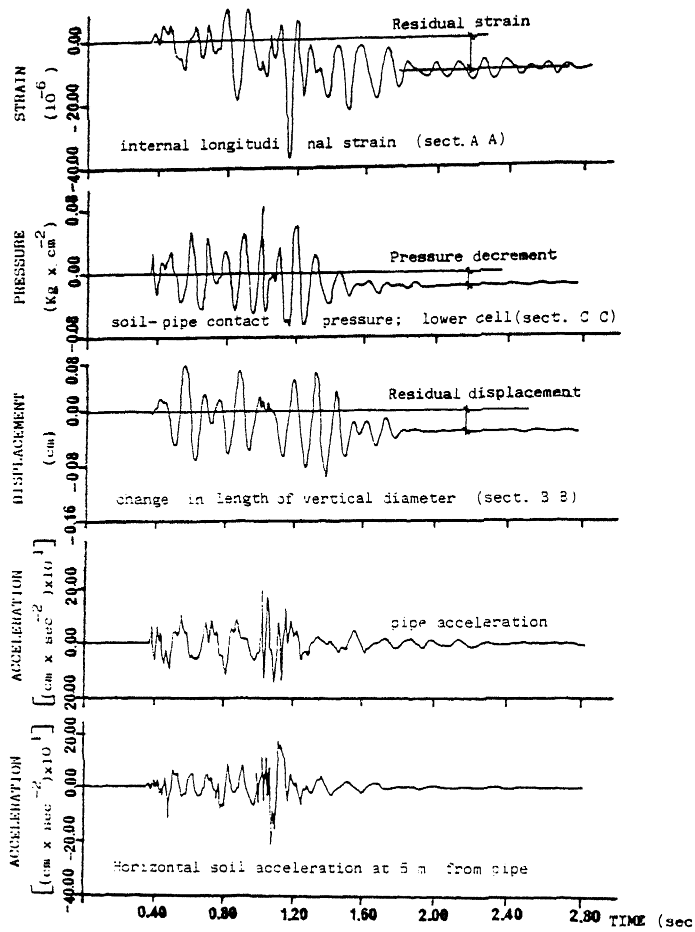

Fig. 3: Examples of time histories recorded during test no 3.

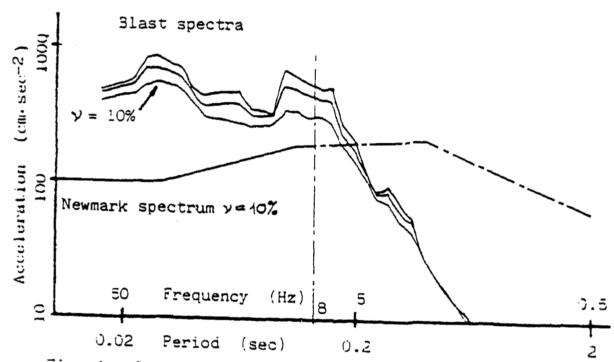

Fig. 4: Ground response spectra for test no 3 at 5 m from pipe axis compared with Newmark spectrum.