THE SEISMIC BEHAVIOUR OF JOINTED PRESTRESSED CONCRETE PIPELINES

F. Brancaleoni (I)
V. Ciampi (II)
A. Samuelli Ferretti (II)
Presenting Author: F. Brancaleoni

SUMMARY

Prestressed concrete buried pipelines are formed by a sequel of comparatively short tubes connected by gasketed joints of considerably low stiffness; their earthquake response cannot hence be immediately reconduced to that of continuous ones, bearing also in mind as seismic danger to concrete tubes comes from possible excessive relative displacements at the joints and not from structural failure. The first part of this paper is devoted to the experimental assessment of basic stiffness and strength properties of such gasketed joints, which are found to show a considerably non linear behaviour, modelled numerically in a specially developed finite element. A formulation for the pipeline-soil dynamic system is then described and implemented in a general purpose nonlinear finite element program. The research is continued analyzing the response of the numerical model to artificial ground motions of opportunely defined spectral shape.

INTRODUCTION

The significance of lifelines behaviour in a seismic environment is presently well understood, as confirmed by the wide attention on the subject, (Ref. 1, 2). For pipelines in particular, a number of papers has been devoted to observed response, to experimental tests and to their analytical modelling (Ref. 3, 4, 5, 6). The latter, mainly concerned with ground-pipe interaction simulation, ground motion input, tubes inertial effects, are in some cases completed by exhaustive numerical results (Ref. 3), so that the literature on the specific subject can be considered satisfactory for engineering purposes and pipeline behaviour in general fairly well assessed.

It must though be remarked as all the above stands for continuous pipes, hence typically for steel ones. Interest is on the contrary herein focused on jointed gasketed large diameter pipelines, for which prestressed concrete elements of the kind shown in fig. 1 are usually employed. The detail of a typical connection is shown in fig. 2.

In this more restricted field in fact only a few researchers have proposed

(I) Researcher, Istituto di Scienza delle Costruzioni, Rome, Italy

(II) Associate Prof., Istituto di Scienza delle Costruzioni, Rome, Italy

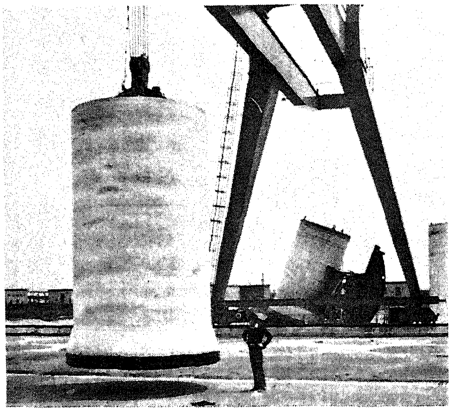

Fig. 1

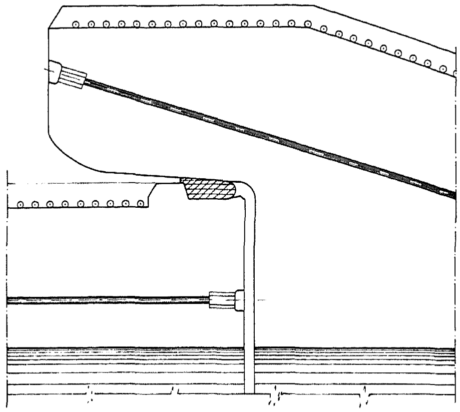

Fig. 2

formulations either derived via questionable assumptions from continuum models (Ref. 4) or based upon finite element approaches (Ref. 3, 5). Ref. 3 includes also quantitative results, which turn out to be of limited design interest because obtained for tube-joint stiffness ratios out of pratical ranges. It must also be pointed out as the above quoted paper reports the response only in terms of forces, while seismic danger for jointed concrete pipes comes from a possible excess of relative displacements, which can cause impact or slippages, the latter with obvious loss of serviceability.

The first part of this paper refers on the results of a number of full scale and laboratory tests aimed at the determination of the cyclic response of the gasketed joints. The observed behaviour has subsequently been modelled in a special "connection" finite element. A finite element formulation for the dynamic pipeline-soil system modelling is also proposed and implemented in a general purpose nonlinear code (Ref. 7). The research continues with a number of applications referring to different soil properties and to different seismic inputs, defined by artificial ground motions of given spectral shapes.

EXPERIMENTAL TESTS

As already mentioned, little data (Ref. 8) are available in the literature on the stiffness properties and on the cyclic behaviour of gasketed joints, as remarked also in other recent papers (Ref. 5). This section aims at providing such information, referring on laboratory and full scale tests performed on the type of connection shown in Fig. 2.

Laboratory tests

The laboratory experimental set up is shown in fig. 3 and comprises three 300 x 300 mm r.c. elements whose sectional shape reproduces a set of four straightened gasket niches. Such elements are sided by two teflon covered steel plates having the task of avoiding possible extrusion of the rubber during the tests. The gasket portions (32 mm diameter, 270 mm unstrained length) are set in place under axial tension, as it happens in reality, and then transversally compressed between the concrete elements by four dynamometric bars until the design geometrical arrangement of the joint is reached. During the compression the rubber shows the usual hyperelastic behaviour, exaggerated by the confinement, which is not reported because of scarce significance in this context. The central concrete element is then connected to a two-way jack and subjected to imposed cyclic displacements. A so obtained average hysteresis loop is shown in fig. 4. As rubber behaviour has been found to be fairly elastical, the small amount of permanent displacement observed is thought to be due to slip and rolling of the gasket within the niche. Forces are due both to rubber elastic deformation and to friction. The overall joint behaviour, due to the inclined shape of the external concrete face indispensable for on site assembling, is hardening for joint closing and softening for joint opening. One point warrants discussion: the absence in the tests of hydraulic pressure which, as the rubber is nearly thriaxially confined, increases the gasket-concrete contact pressure and can hence vary the stiffness of the joint. As hydraulic pressures are inferior by an order of magnitude to the basic contact ones, their absence is thougth to be negligible. This has been confirmed by their simulation through an equivalent increase of vertical compression, which has caused variation of results within experimental uncertainties.

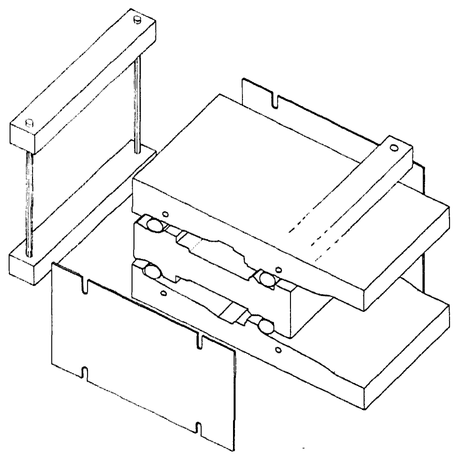

Fig. 3

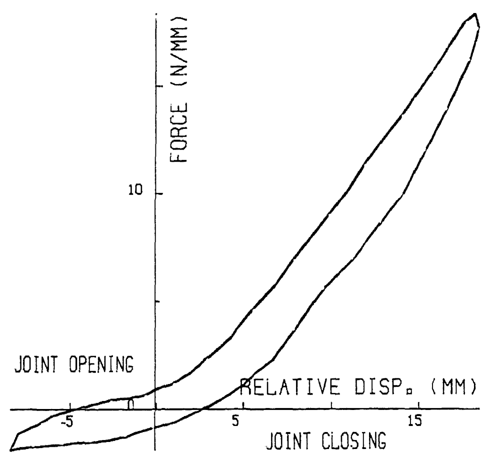

Fig. 4

Full scale tests

Aiming both at a corroboration of the previous results and at their extension to pipe impact and complete slippage, which could not be simulated by the laboratory model, one full scale test on 1800 mm diameter pipes has been carried out. The experimental set up, shown in fig. 5, comprised two pipes placed on four wheel rollers and connected by a two-way jack pinned at both ends to two transversal steel bars fixed to the pipes. Displacements were measured in three points along the circumference and reported results refer to their average. A series of typical experimental cycles is shown in fig. 6, where several representative branches are indicated: loading (A), unloading (B), reloading (C) up to concrete impact (D) are self explanatory and it must only be noted as the reloading shape

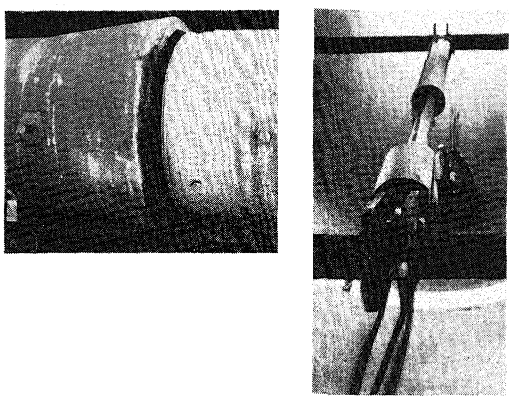

Fig. 5

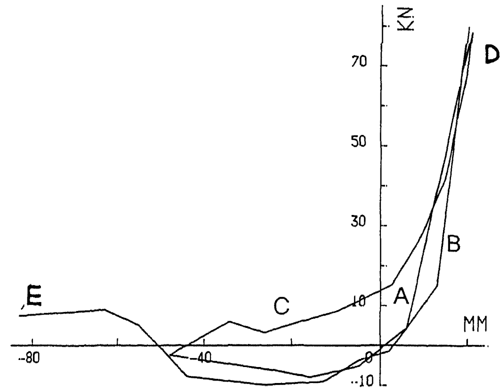

Fig. 6

indicates again clearly the slippage origin of permanent displacements. Branch E (slippage) exhibits on the contrary an unusual force sign inversion which takes place when the gasket passes over the terminal smaller concrete swelling and, being elastically deformed, "pushes away" the tubes thus releasing to the system the energy accumulated during the assembling procedure.

Finally, fig. 7 shows together, in the same scale and in the same displacement range, the laboratory and the full scale test results, given per unit length of gasket. The agreement is entirely satisfactory. In the same figure is also shown a piecewise linear elastic curve adopted for the numerical modelling and discussed in the next section.

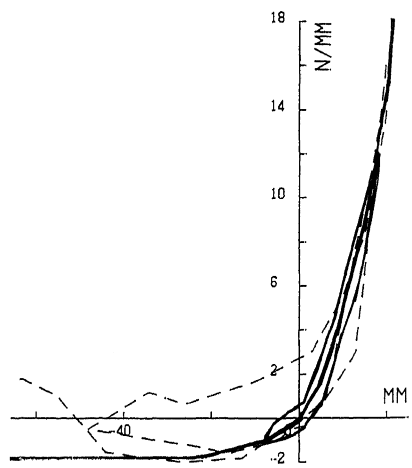

Fig. 7

NUMERICAL MODELLING

The joint element

All six relative displacements components are permitted between adjacent pipes, but not all of them are of interest from a seismic point of view. Only longitudinal relative displacement and rotation about a vertical axis perpendicular to the pipeline are considered here. The other four components are neglected for different reasons. Relative rotation about a longitudinal axis is obviously of scarce importance; the rotation about an horizontal axis perpendicular to the pipeline can be significantly excited only by vertical ground motion which gives negligible effects in the axial direction. As the latter are known to be prevailing (Ref. 2, 3), the motion in a vertical plane has not been included in the formulation. The two components left, i.e. transversal relative displacements, can also be excited, but the transversal stiffness of the gasketed joints is high enough to proclude tube impacts in this direction, while possible overstresses due to non axisymmetrical gasket compression have, in the authors experience, been found to be easily accounted for in a proper joint design.

In the herein proposed finite element approach it was indispensable to model the gasketed joint by a "connection" element permitting only the two above said relative displacements. The considerably nonlinear experimental behaviour described in the previous sections has been simulated by the elastic piecewise linear curve shown in fig. 7, so neglecting energy dissipation in the gaskets; such approximation is acceptable because most damping in this type of problem comes from soil hysteretic behaviour.

The 4 x 4 stiffness matrix of the element is full, due to non linearity. The terms of each 2 x 2 submatrix are readily found by opportune integration along the circumference of the forces generated in the gasket about a given deformed configuration. The derivation operations needed to determine local tangents to force-displacements curves are carried out numerically, while integrations along the circumference are calculated in closed form. The element has been implemented in the already mentioned code (Ref. 7).

Equations of motion of the pipeline-ground system

The non-linear equations of motion of the pipes-joints-ground system are expressed in terms of absolute displacements, more convenient from an engineering point of view, as

$$\underline{M}\,\ddot{\underline{U}} + \underline{D}\,\dot{\underline{U}} + \underline{S} = \underline{k}_s\,\underline{u}_g + \underline{D}_s\,\dot{\underline{u}}_g \qquad (1)$$

where $\underline{S}$ is a structural reactions vector, $\underline{k}_s$ is the linear soil stiffness matrix, $\underline{D}_s$ is the soil dissipation matrix, $\underline{u}_g$, $\dot{\underline{u}}_g$ are input ground displacements and velocities respectively and with obvious meaning of the other symbols. The derivation of eqs. (1) is straightforward and is hence not given, see e.g. (Ref. 3), while the various terms are briefly described in the following.

The inertia matrix $\underline{M}$ comprises contributions of pipe mass, water mass for the terms related to transversal motion only, plus a "transported" soil mass. Water masses are omitted for the longitudinal motion as water is a practically inviscid fluid; transported soil mass terms $\bar{m}_i$ are evaluated (Ref. 9) as

$$\bar{m}_i = \rho \int_{c_i - \frac{l_i}{2}}^{c_i + \frac{l_i}{2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (\psi_x^2 + \psi_y^2 + \psi_z^2)\, dx\, dy\, dz$$

where ρ is the soil massdensity, c_i is the relevant coordinate of joint i, l_i the corresponding pipeline length and ψ_x, ψ_y, ψ_z the soil displacement fields in the longitudinal, transversal and vertical directions respectively when subjected to the forces transmitted by the pipeline, normalized so as to have unitary relative displacements.

The dissipation matrix $\underline{D}$ comprises only soil damping contributions, i.e. $\underline{D} \equiv \underline{D}_s$, and is stiffness proportional. The proportionality coefficient is evaluated in accordance to the plain strain, deep embedment complex dynamic soil stiffness expression reported in (Ref. 3).

The structural reactions vector is evaluated at each time step as $S = (\underline{k}_p + \underline{k}_s)\underline{U}$, where $\underline{k}_p$ is the linearized pipeline stiffness matrix comprising linear beam element terms from the pipes plus linearized joint elements terms as described in the previous paragraph. The soil contribution $\underline{k}_s$ is calculated on the basis of the three dimensional Mindlin's solution, as exposed in (Ref. 9).

Finally, $\underline{u}_g$ and $\dot{\underline{u}}_g$ are calculated for each relevant degree of freedom taking into account the wave propagation velocity of soil, assumed equal to the shear velocity $\sqrt{G/\rho}$. In this work artificial ground motion input of given spectral shape has been used as seismic input.

The solution of eqs. (1) is carried out via direct time integration, using the Newmark's algorithm.

Examples of application

The pipeline examined is composed of elements identical to that shown in figs. 1,2, with 3000 mm internal diameter and 200 mm thickness. The numerical model comprises a sequel of sixty pipes of 6000 mm length each. The total length analyzed has been determined after a number of preliminary tests and has been found to be more than adequate to describe the phenomenon. The same tests have shown the effects of the off-diagonal soil stiffness terms to be negligible, in agreement with the results of (Ref. 3, 9); they have hence been omitted in the cases presented.

The ground motion input used has the 5% damping acceleration response spectrum shown in fig. 8 and the ground acceleration history of fig. 9, with a peak value of .25 g . In the examples an earthquake direction-pipeline axis angle of

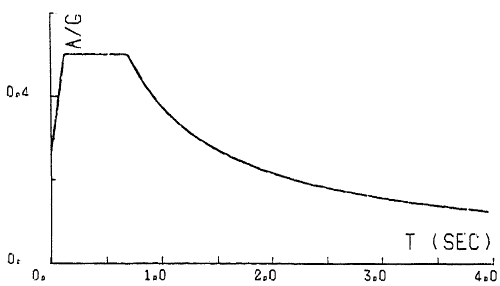

Fig. 8

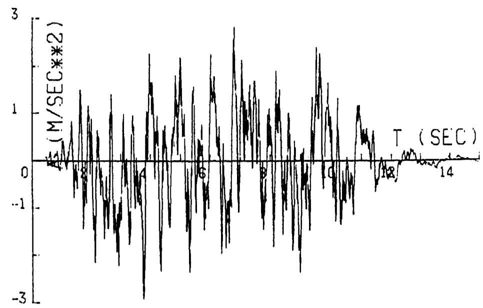

Fig. 9

45° has been used.

The applications have been carried out for two different soil properties, identified as soft soil ($E = 100\ N/mm^2$, $\nu = 0.3$) and medium soil ($E = 1000\ N/mm^2$, $\nu = 0.3$), having a shear wave velocity V of $\sim$160 and $\sim$500 m/sec respectively. The maximum strains in the soil $\varepsilon_{max} = \dot{u}_{max}/V$ due to elastic wave propagation effects when subjected to the earthquake of fig. 9 are of $\sim$0.0015 and $\sim$ 0.0005 respectively, while their components in the pipeline direction are $\sim$ 0.001 and $\sim$ 0.00035.

For the soft soil case, three different mass values have been considered: no mass (quasi - static case), pipeline mass only, pipeline plus transported soil mass. The results for the first two cases are practically identical, while the introduction of the transported mass induces differences up to a maximum of $\sim$ 10% and is hence small but not negligible. All the results reported in the following include transported mass contributions.

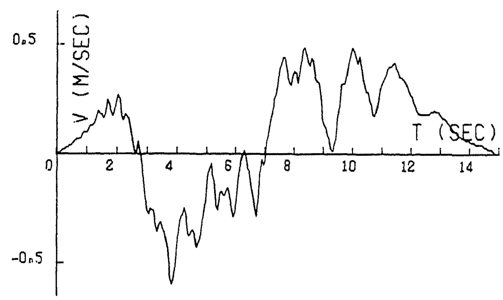

Fig. 10

The response for a number of variables, compared with the input ground velocity time history (fig. 10), is reported in figs. 11 ÷ 14. Figs. 11 and 12

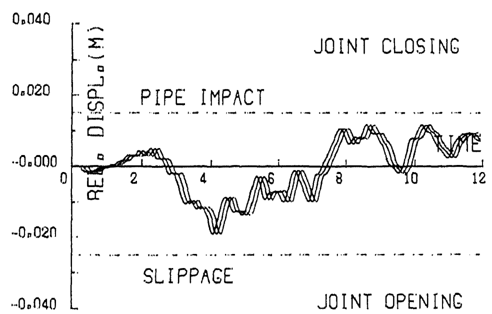

Fig. 11

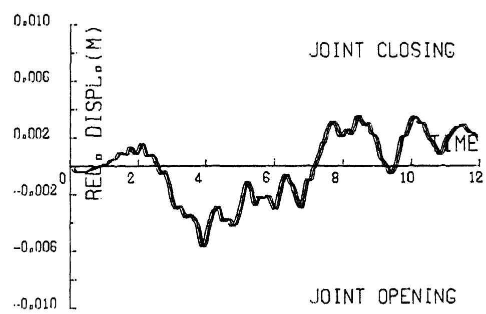

Fig. 12

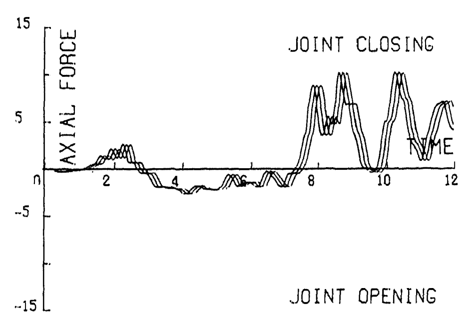

Fig. 13

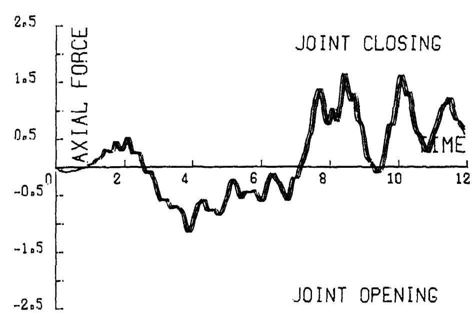

Fig. 14

show the relative displacement time histories of three typical equally spaced joints for soft and medium soil respectively. The similarity with the velocities is evident, but is to be noted a trend towards the joint opening, more pronounced for the soft soil. For the latter case, which presents higher relative displacements, the pertinent impact and slippage limits are also shown. The trend towards joint opening is explained observing the axial force time histories in the same joints, figs. 13 and 14, for soft and medium soils respectively. Due to the non linear behaviour of the gaskets, forces are much higher for joint closing then for joint opening, as it is evident specially for the soft soil, and produce the above said effect.

Finally, it is important pointing out as strains in the pipes, ~ 0.000013 and ~ 0.000083 for soft and medium soil respectively, are much lower than elastic wave propagation values previously given.

The following concluding remarks can be made: displacements are concentrated at joints with considerable reduction of axial and flexural forces in pipes; flexural effects, although not reported here for lack of space, are considerable due to the large pipe diameter; pipe slippage at joints appears as the most likely cause of loss of serviceability; a more complete numerical investigation is needed including a wide variation of seismic input and soil parameters.

ACKNOWLEDGEMENT

This work has been carried out with the collaboration and support of VIANINI INGEGNERIA S.p.A., Rome. Facilities and support for the field tests have been provided by VIANINI INDUSTRIA S.p.A., Rome.

REFERENCES

1. "The Current State of Knowledge of Lifeline Earthquake Engineering", ASCE, New York, 1981.
2. Ariman T., Muleski G.E.: "A review of the response of buried pipelines under seismic excitation", Earthq. Eng. Struct. Dyn., Vol. 9, 133-151, 1981.
3. Hindy A., Novak M.: "Earthquake response of underground pipelines", Earthq. Engng. Struct. Dyn., Vol. 7, 451-476, 1979.
4. Parnes R., Weidlinger P.: "Dynamic response of an embedded pipe subjected to periodically spaced longitudinal forces", Grant Report No. 13 to the National Science Foundation, 1979.
5. Wang L.R.L.: "Seismic evaluation model for buried lifelines", in (Ref. 2).
6. Wang L.R.L., Cheng K.M.: "Seismic response behaviour of buried pipelines", J. of Press. Vessel Tech., ASME, Vol. 101, 21-30, 1979.
7. Mondkar D.P., Powell G.H.: "ANSR-General Purpose Program for Analysis of Nonlinear Structural Response", EERC Report 75-37, Berkeley, 1975.
8. Krathy R.S., Salvadori M.G.: "Strength and dynamic characteristics of gasket jointed concrete water pipelines", Grant report No. 5 to the National Science Foundation, Wedlinger Ass., 1978.
9. Penzien J.: "Soil - pile foundation interaction", in Earthquake Engineering, (Ed. R.L. Wiegel), Prentice - Hall, N.J., 1970.