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APPLICATION OF THE FINITE DIFFERENCE TECHNIQUE TO THE ANALYSIS OF FLEXIBLE RISER SYSTEMS

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Flexible pipes and risers are critical components of offshore field developments because they provide the means of transferring fluid or power between individual subsea modules and a topside floating platform. These risers are designed to carry tensile forces and accommodate floating platform motion at the sea surface by being flexible. They are consequently manufactured to possess high structural axial stiffness and relatively low structural bending stiffness. When considered in an offshore environment, these structural properties provide a very small resistance to disturbances caused by wave and current induced hydrodynamic loadings. Hence their behaviour can be said to be more mechanical rather than structural and can be predicted very efficiently using a finite difference numerical solution scheme - this scheme is particularly suited to these types of structures.

This paper presents descriptions and a practical application of efficient numerical methods for static and dynamic response analysis of flexible riser systems. The static method employs a dynamic relaxation technique coupled with kinetic damping whereas the dynamic method employs an optimised finite difference scheme incorporated with an implicit and therefore an unconditionally stable time integration algorithm. The structural behaviour of single and multiple flexible riser systems is examined and some of the problems associated with flexible risers regarding their mechanical behaviour and manufacturing materials are discussed.

INTRODUCTION

Governing equations of motion for a transient structure are a function of space and time. The numerical solution of the equations is carried out by discretising them in space using finite element or finite difference techniques and in time using explicit or implicit algorithms. Finite element schemes can be generally applied to the analysis of any type of structure but the solution scheme requires the assembly of overall structural properties which makes the analysis lengthy and expensive. On the other hand, application of finite difference schemes is limited to a particular type of structures, however these schemes are very fast and therefore cost-effective.

One of the problem areas in which finite difference schemes can be successfully applied is the analysis of flexible structures such as cable, membrane, pipeline and riser structures. These systems, due to their flexibility, show very small structural resistance to force induced responses and therefore their behaviour can be efficiently predicted using a simple discretisation method like a finite difference lumped mass scheme.

Flexible riser systems are a fairly recent innovation in offshore oil and gas technology. They are commonly used within a floating production system to transfer fluids or power between the subsea equipment and the surface vessel. The main reason for developing the technology is that the system is inherently dynamic and is designed to withstand large deflections due to wave action and vessel motions. This alleviates the need for complex motion compensation equipment on the vessel.

The analysis of flexible riser systems was initally carried out by employing the widely used matrix based scheme (finite element) but recently the trend is towards the use of finite difference schemes. These schemes are at least one order of magnitude faster than finite element schemes in computing time and also require much less memory capacity. The validity of the finite difference approach has been confirmed by comparison with results from experiment and from finite element schemes (Ref. 1, 2, 3).

The present paper describes methods based on the finite difference technique to analyse any flexible structure with emphasis on application to analysis and design of flexible riser systems.

CHARACTERISTICS OF FLEXIBLE RISER SYSTEMS

The purpose of a flexible riser system is to transfer hydrocarbons or other fluids associated with oil production between a floating vessel and the seabed. A typical flexible riser system comprises of a continuous length of pipe attached at one end to a floating vessel, hanging in a catenary shape to some type of buoyant component positioned at some distance along the length and then approaching the seabed either smoothly or at a near vertical angle. Schematics showing typical configurations are presented in Figure 1.

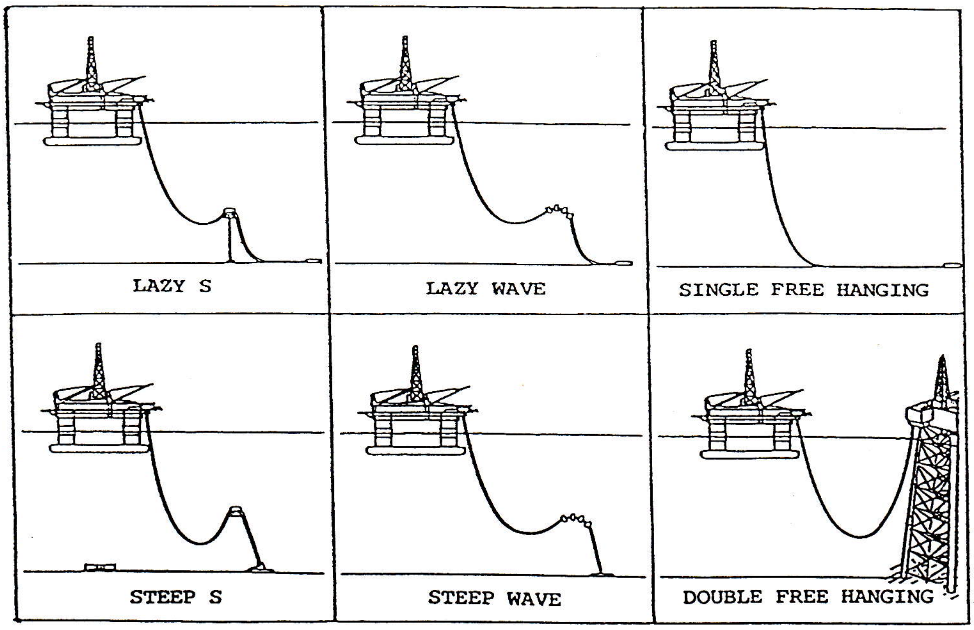

Figure 1 Typical types of Flexible Riser Configuration

Flexible pipe is defined as a composite of layered materials which form a pressure containing conduit. The pipe structure allows large deflection without a significant increase in bending stresses (Ref. 6). The pipe is therefore designed such that it has a low bending stiffness and can accommodate high internal and external pressures. The pipe construction will either be of a "bonded" type (whereby layers are bonded together using adhesive and are then vulcanized in an oven to form a homogeneous structure) or "non-bonded" (whereby individual layers remain separated allowing internal relative movements). Typical materials used for construction include: polymers, textile, steel and fabrics.

From an engineering analysis point of view, the technical characteristics of a flexible riser system are:

- tension dominated structure;
- hydrodynamic loading due to waves and current;
- dynamic boundary condition due to movement of vessel;
- pinned/clamped boundary conditions;
- system can be partially in air/partially submerged;
- possible connection to a subsurface body;
- possible change in weight along length of system;
- possible surface contact at seabed.

On consideration of the above characteristics the main complexity in the analysis of flexible riser systems is due to non-linearities arising from hydrodynamic loading and dynamic boundary conditions.

CLASSIFICATION OF PROBLEMS AND METHODS OF ANALYSIS

This paper is concerned with large deflection analysis of tensile structures subjected to dynamic boundary conditions and non-linear loading conditions. Analysis of flexible structures subjected to dynamic loading is performed in two stages: static analysis and dynamic analysis. The methods used in these two stages are now described.

Static Analysis and Start-Up Procedure

The static equilibrium configuration of a system is computed using a dynamic relaxation technique incorporated with kinetic damping. In this technique the structure is initially laid in a flat plane. The ends are then lifted to the correct static positions and static loads are applied to the system. The riser is allowed to respond without viscous damping and each time a kinetic energy peak is detected all nodal velocity components are set to zero and the system is restarted. Eventually the kinetic energy of the system reduces to practically zero - the system is then in static equilibrium. The theory of the static solution scheme is given in Ref. 4.

Dynamic Analysis and Static-Dynamic Interface

Dynamic solution of the equations of motion is achieved by using the computed static solution as the starting configuration for a dynamic solution scheme. This scheme uses an optimised finite difference technique incorporated with an implicit and therefore an unconditionally stable time integration scheme. The theory of the scheme is given in Ref. 5.

Hydrodynamic Loading

Environmental loads within flexible riser analysis are represented mathematically by the modified Morison equation (Ref. 7). This equation gives an expression for the total force per unit length on an inclined moving cylinder within a fluid velocity and acceleration field. The force is split into a drag component and an inertia component as represented in equation (1).

$$F = F_d + F_m \tag{1}$$

where F is the total force per unit length perpendicular to the cylinder axis

F_d is the hydrodynamic drag component of F

F_m is the hydrodynamic inertia component of F

The drag and inertia components given in equation (1) are represented in equations (2) and (3) respectively.

$$F_d = (1/2)\,\rho\, C_d\, D \left| V_n - \dot{X}_n \right| (V_n - \dot{X}_n) \tag{2}$$

and

$$F_m = \rho A C_m \dot{V}_n + \rho A (C_m - 1) \ddot{X}_n \tag{3}$$

where ρ is the fluid density

C_d is the hydrodynamic drag coefficient

C_m is the hydrodynamic inertia coefficient

D is the outside diameter of the cylinder

A is the cross-sectional area of the cylinder

V_n is the fluid velocity normal to the cylinder axis (a combination of current and wave induced velocity)

$\dot{V}_n$ is the fluid acceleration normal to the cylinder axis

$\dot{X}_n$ is the structural velocity normal to the cylinder axis

$\ddot{X}_n$ is the structural acceleration normal to the cylinder axis

All terms in equations (2) and (3) must be known before a solution can proceed. Slender structures, such as flexible risers, are drag dominant and the inertia term in equation (3) is usually negligible for the riser itself. However, the response of other components in the system, for example the buoyant arch in the "Steep-S" system (see Figure 1), may be governed by the inertia term in equation (3). A thorough treatment of the mechanics of wave forces on offshore structures is given in Ref. 8.

All terms in equations (2) and (3) are now discussed. The fluid density, outside diameter and cross-sectional area in equations (2) and (3) are known. The selection of drag and inertia coefficients is based on Reynold's number and Keulegan-Carpenter number (Ref. 8) and can be considered as known.

The fluid kinematics are based on a combination of current- and wave-induced velocities and wave-induced accelerations. A deterministic approach is usually adopted and the flexible riser system is designed to withstand a given "design wave" with a particular return period (e.g. a probability of occuring once in one hundred years - the "100 year" wave). This approach implies a single wave analysis using a wave with a known height and period. The fluid velocity and acceleration field are then defined by means of a suitable wave theory (Ref. 8), for example regular (Airy) theory.

The only outstanding variables in equations (2) and (3) are the structural velocity and acceleration. These variables define the structural response of the system and it is the non-linearity in drag force in equation (2) that causes the main problem in solution of the equation of motion.

DESIGN OF FLEXIBLE RISER SYSTEMS

Efficient design of flexible riser systems is only made possible by using fast computer-based solution techniques as described previously. The basic steps required in design of a flexible riser system are set out in this section.

Design Criteria

The design of flexible riser systems is usually based on allowable pipe curvatures and tensions, which are prescribed by the pipe manufacturer, and clearances between the riser and other structures and boundaries during its dynamic response. The allowable curvatures and tensions are based on full-scale test procedures and stress analysis carried out by the manufacturer and these limits ensure that the pipe is not over-stressed when responding to dynamic loads and vessel motions. The system is generally designed such that the pipe is always in tension throughout its dynamic response cycle. Minimum clearances are also specified to avoid clashing problems between riser-seabed or riser-vessel and between the riser and other adjacent risers, cables or mooring systems.

Design Parameters

The main problem in design of flexible riser systems is that the number of design parameters is large. The environmental conditions, vessel motions and riser properties are usually well-defined. The main design parameters are therefore the choice of configuration, the length of riser, the system geometry and the sizing of buoyancy modules, subsurface buoy or arch. The choice of configuration (possible configurations are presented in Figure 1) is usually based on economic criteria, position of wells etc. and can be considered as known. The length of riser, sizing of buoyancy components and system geometry need to be determined by the designer.

Design Procedure

The first stage in the design of a flexible riser system is to determine an acceptable system layout. This first stage is based on static analysis and it is normal to carry out a parametric study to assess the effect of changing the design parameters (i.e. system geometry and length) on the static curvature and tension. Based on the results of this parametric study, the designer selects a suitable range of system geometries and lengths that satisfy the design criteria. The parametric study will also assess the static effects of vessel offset (displacement of the top end) and current loading in different directions.

The second stage in the design procedure is to perform dynamic analysis of the system to assess the global dynamic response. A system layout and length is chosen from stage one and a series of dynamic loadcases are considered. These loadcases combine different wave and current conditions, vessel positions and riser contents in order to provide an overall assessment of the riser suitability in operational and survival conditions. The corresponding analyses are then carried out and dynamic curvatures, tensions and clearances are checked against the design limits. The design may need to be modified at any stage of this procedure - it is therefore essential that the solution technique is fast.

The third stage in the design procedure is to perform detailed static and dynamic analyses of local areas to design particular components. This stage is presented in a separate publication (Ref. 9).

PRACTICAL APPLICATIONS

A numerical scheme based on the described general method has been implemented into an analysis package called "FLEXRISER". The program efficiently simulates the static and dynamic behaviour of single and multiple flexible riser systems and is used by operators, contractors, manufacturers and consultants within the offshore industry. Results from two practical flexible riser systems are presented.

The first system considered consists of a flexible riser with sub-surface distributed buoyant modules attached down the riser length ("Steep Wave"). The system is subjected to wave and current flow in the direction defined from vessel to seabed connector and vessel excitation at the top end.

A schematic of the system layout and key data is presented in Figure 2. Typical results from dynamic analysis are presented in Figures 3 to 6. The response of the system during a wave cycle is presented in Figure 3 - this type of diagram is called a "snapshot". The extreme values of tension and curvature along the length of the riser system during a wave cycle are presented in Figures 4 and 5 respectively. The time variation of tension at the vessel end of the system is presented in Figure 6.

The second system considered consists of two different flexible risers connected to a single common sub-surface buoy ("Lazy-S"). A schematic of the system layout is presented in Figure 7. The system is subjected to wave and current flow perpendicular to its plane and corresponding vessel excitation.

The dynamic response of the system during a wave cycle is presented as a series of "snapshot" diagrams in Figures 8, 9 and 10. These figures show the system response from the side, end and plan views respectively.

PROBLEM AREAS

Flexible risers transport hot, high-pressure mixtures of oil, water, gas, sand and various contaminants. These systems are robust and cost-effective engineering devices for production of hydrocarbons in deep waters. However, there are uncertainties and limitations in using flexible riser systems for various situations and research is currently being carried out by manufacturers to investigate the associated problems. The following areas are currently being researched:

- performance of risers under axial compression - flexible risers are designed to carry only tensile forces. If the riser is subjected to severe compression, the change in mechanical properties and the riser behaviour is uncertain;

- flow of hot oil - flexible risers are tested and their materials are designed for content temperatures up to approximately 130^{o}C. Recently, however, temperatures up to 250^{o}C have been recorded;

- transportation of gas - confidence in impermeability of the riser material for gas porosity is not absolute.

CONCLUSIONS

Efficient finite difference techniques have been applied to solve static and dynamic problems in offshore flexible riser analysis. These techniques help the designer to quickly assess a wide variety of loadcases and to optimise the design parameters accordingly. Application of the techniques has resulted in a software package called "FLEXRISER" which is widely used within the offshore industry.

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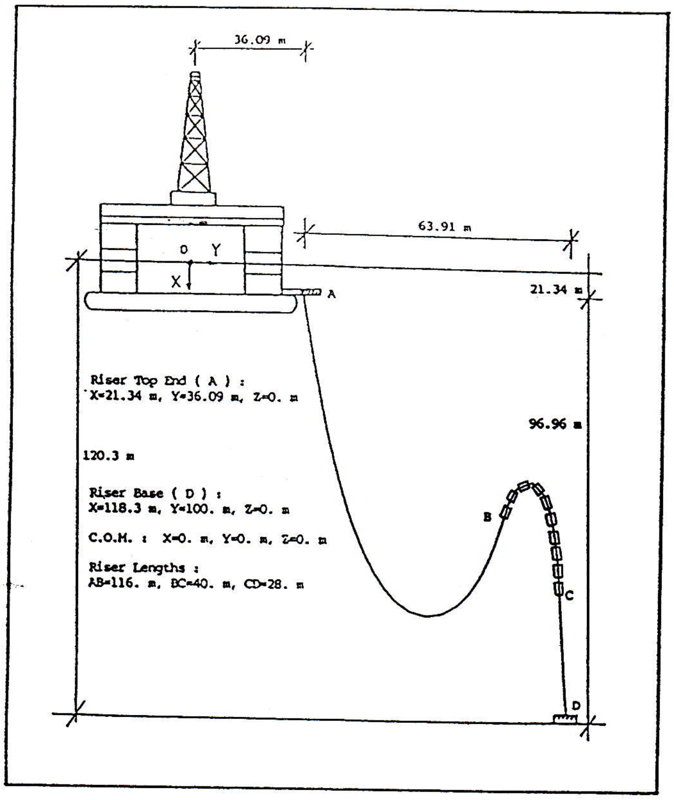

Figure 2 Steep Wave Configuration - Layout

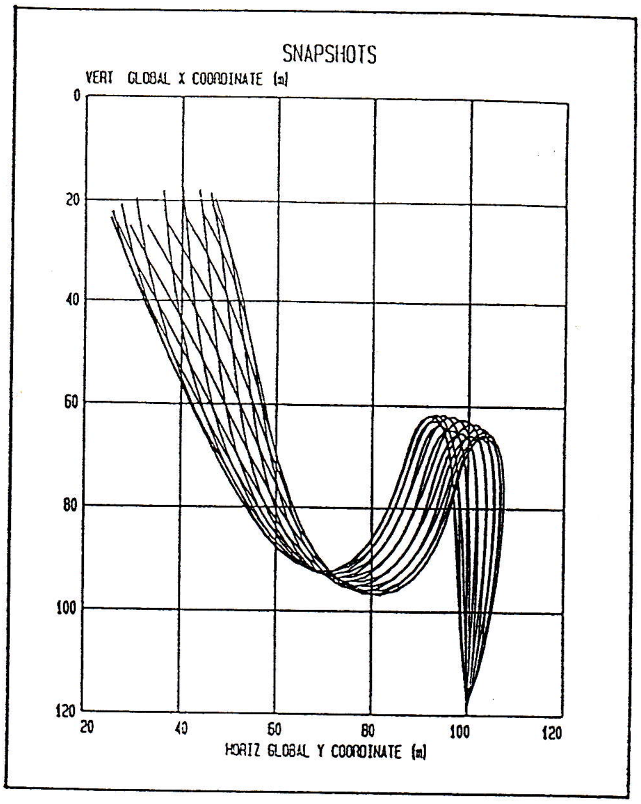

Figure 3 Steep Wave Configuration - Snapshots

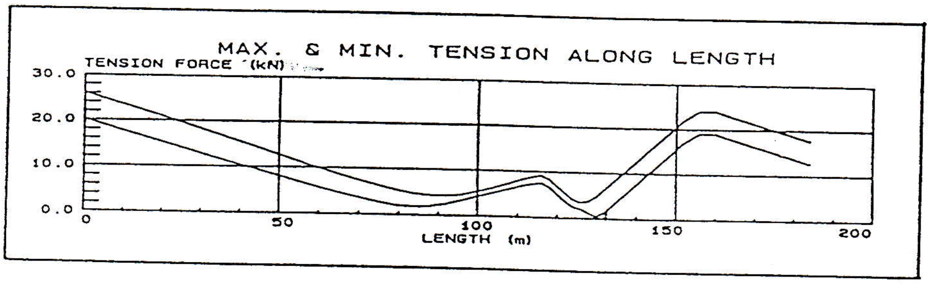

Figure 4 Steep Wave Configuration - Envelopes of Tension

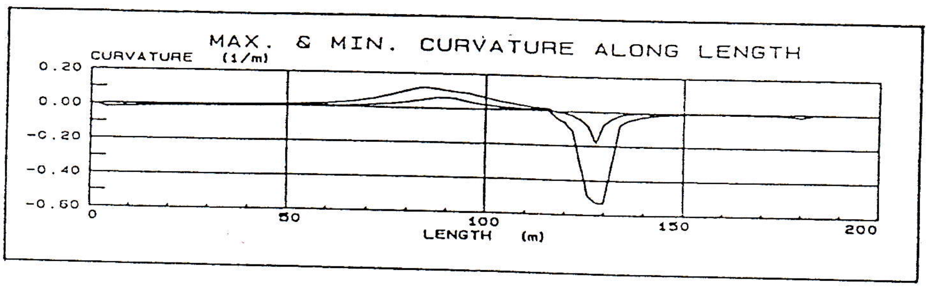

Figure 5 Steep Wave Configuration - Envelopes of Curvature

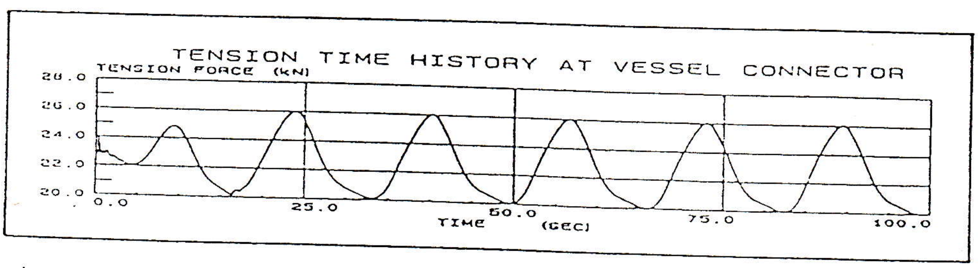

Figure 6 Steep Wave Configuration - Time History of Tension at Vessel Connector

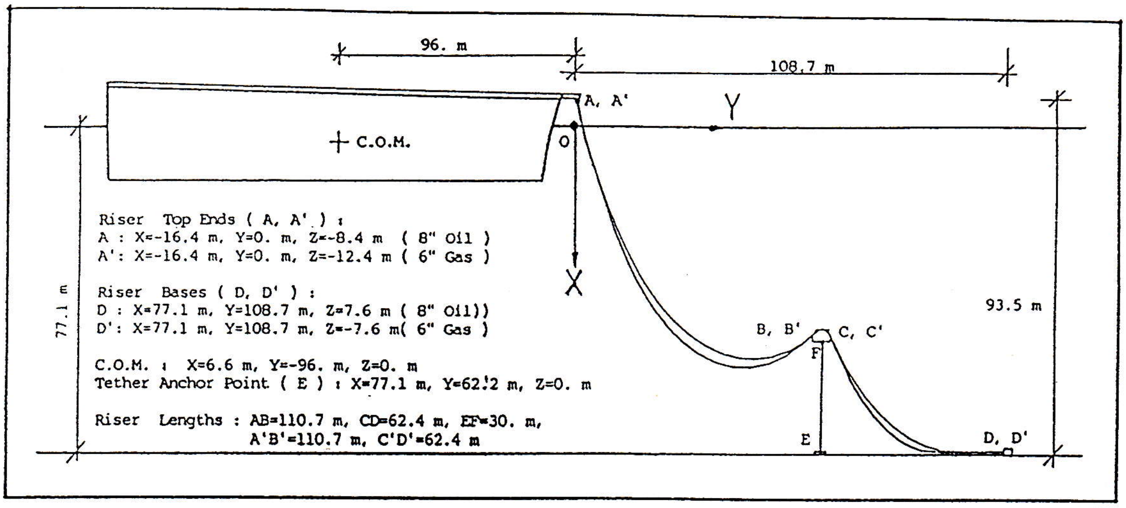

Figure 7 Multiline Lazy-S Configuration - Layout

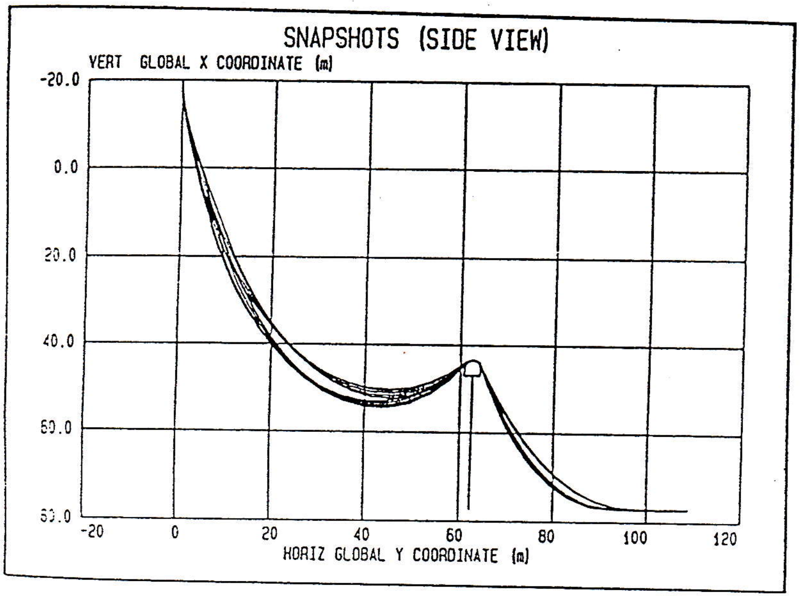

Figure 8 Multiline Lazy-S Configuration - Snapshots (Side View)

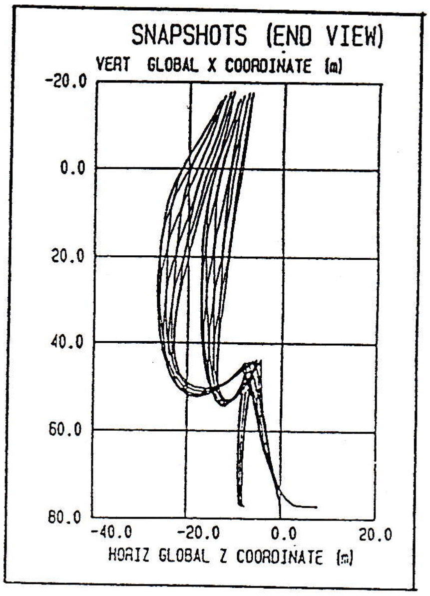

Figure 9 Multiline Lazy-S Configuration - Snapshots (End View)

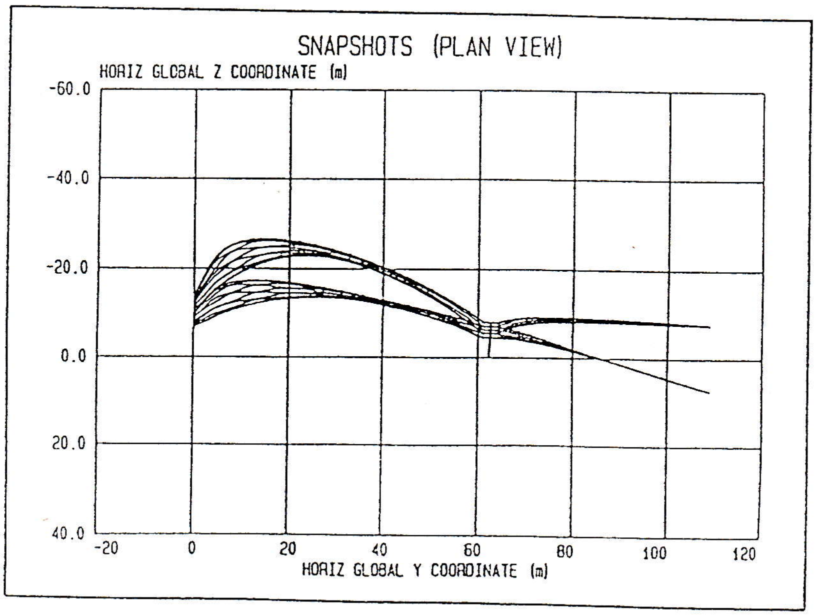

Figure 10 Multiline Lazy-S Configuration - Snapshots (Plan View)

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