

# Parametric Modeling of Static Three-Dimensional Problem of Buried Pipeline through the Coupling between a Finite Cylindrical Shell Element and Special Boundary Elements

Raimundo A. Menezes Junior<sup>1</sup>, Moises M. Salvino<sup>2</sup>, Carlos L. dos Santos<sup>2</sup>, Allan R. Albuquerque<sup>2</sup>, Jailson M. Ferreira<sup>3</sup>, Dawy Keyson<sup>4</sup> and Carlo R. Lima Martin<sup>3</sup>

*1. Alternative and Renewable Energy Center, Federal University of Paraiba, João Pessoa 58051-900, Brazil*

*2. Technology Center, Federal University of Paraiba, João Pessoa 58051-900, Brazil*

*3. Federal Institute of Education, Science and Technology of Paraiba, João Pessoa 58051-900, Brazil*

*4. Education Center, Federal University of Paraiba, João Pessoa 58051-900, Brazil*

**Abstract:** This work deals with an application in parametric modeling of problems regarding pipelines buried in static system, written in C++ using ObjectARX functions. The application is fully integrated with AutoCAD through saproms.dll and saproms.arx libraries where the stages of pre-processing, processing and post-processing are done in AutoCAD software environment itself without having to export data to another processing environment. The analysis processing is done by functions whose algorithms are based on the solution of the coupling between the FEM (finite element method) and the BEM (boundary element method). The representation of the homogeneous pipeline is made by the FEM using a finite element in the form of a cylindrical panel called CYS (cylindrical shell), developed from the homogeneous isotropic model proposed initially by Djoudi Bahai, who uses the philosophy of the assumed deformation model (assumed strain based model). The soil is taken to be a continuum infinite or semi-infinite elastic solid patterned by BEM where special boundary elements are proposed with curved surface or curved edges to represent the soil-structure interaction mainly in the areas of contact with the pipeline.

**Key words:** Finite elements, boundary elements, AutoCAD.

## 1. Introduction

Due to the need for implementation and improvements in its infrastructure, industry in various fields has boosted the growth of the use of buried and submerged pipelines in recent years, such as oil and gas and the like. On account of interacting with other media (soil, liquid, etc.), these structures have a high degree of complexity, which requires special attention from initial conception to actual operation. Thus, in recent decades, designers have used some

aid tools to produce more efficient buried pipeline projects. One of the important lines is based on the accumulated experience that is usually described in predetermined regulations. However, this is not enough, as each project has its own peculiarities. So in many cases, a series of experimental tests are specified to extract some parameters of buried pipeline behavior (pipeline displacement versus share of pipeline laying, etc.). However, even with the great help of the experimental apparatus, there are still issues which play an important role in problem behaviors that are not generally addressed thoroughly, such as the state of deformation and stress in the pipeline and its interaction with the soil.

---

**Corresponding author:** Raimundo A. Menezes Junior, Ph.D., research field: numerical methods for structures. E-mail: jrmeneses@cear.ufpb.br.

Thus, the third line of tools that can be potentially used is the numerical simulation techniques enabling the structural analysis of the problem [1-7]. The mathematical models commonly used are usually restricted to two-dimensional space. If the analysis region of the pipeline is lengthy, without significant change in the effect on the neighboring area along the length of the pipeline, the results of the two-dimensional analysis usually do not present significant differences when compared to the three-dimensional model. However, it is not always possible to guarantee that the vicinity of the pipeline remains unchanged, as it usually has to go through urban areas, crossing roads, railways, etc.. Thus, the development and implementation of three-dimensional models for the analysis of buried pipelines is undoubtedly a real need for the improvement of projects [8-14]. In recent decades, many researchers have devoted themselves to the study of mathematical models of interaction composed of a set of sub-models associated with the pipeline, the soil and its interfaces, respectively.

In general, the analytical solutions of the governing equations of buried pipelines are available for more special cases of interaction [15, 16]. This is the case in the one-dimensional class when the buried pipeline is seen as an infinite bar resting on elastic foundation, whose solutions are found in the works of Biot [3] and Hetenyi [11]. There are many semi-empirical methods, which are obtained by incorporating some correction factors in the two-dimensional analytical solutions, which are calibrated experimentally. The most known semi-empirical techniques are: Iowa method and its modified versions. Against this background, in this paper, we present an application in parametric modeling of pipeline problems buried in static system, written in C++ using ObjectARX functions. The application is fully integrated with AutoCAD through saproms.dll and saproms.arx libraries where the stages of pre-processing, processing and post-processing are done in AutoCAD software environment itself without

having to export data to another processing environment.

## 2. Cylindrical Shell Finite Element

Some researchers have presented alternatives in finite elements for the analysis of cylindrical shells. One of these alternatives is based on the assumed deformation (assumed strain-based model) model. Djoudi and Bahai [7, 17] presented the ideas of the model for cylindrical shallow shells employing the theory of shells by Donnell [18]. The finite element CYS employed in this work is based on the philosophy of the assumed deformation model and was initially proposed by Djoudi and Bahai [7, 17]. The CYS element has four nodes with 5° of freedom: three translational ( $u$ ,  $v$ ,  $w$ ) and five rotational ( $\frac{\partial w}{\partial x}$ ,  $\frac{\partial w}{\partial y}$ ) in Fig. 1.

## 3. Special Boundary Elements

In literature review, much of the geometry of the boundary elements is plane or approximated by polynomials, usually up to second degree. Given the specificity of the subject discussed in this work, these would not be very suitable. Therefore, we preferred the new boundary elements in which cylindrical surfaces (C in Fig. 2), plane surfaces (A and B in Fig. 2) with non-polygonal boundaries could be represented exactly. The proposed elements are shown in Fig. 2.

## 4. Application of Parametric Modeling

The problem of buried pipeline is examined from a parametric modeling application to problems of soil-structure interaction that works in AutoCAD software environment. Fig. 3 presents a brief description of the complete problem to be analyzed and the BEM (boundary element method)-FEM (finite element method) used elements. The application was developed in ObjectARX language and its purpose is to make the generation of meshes, which discretize the

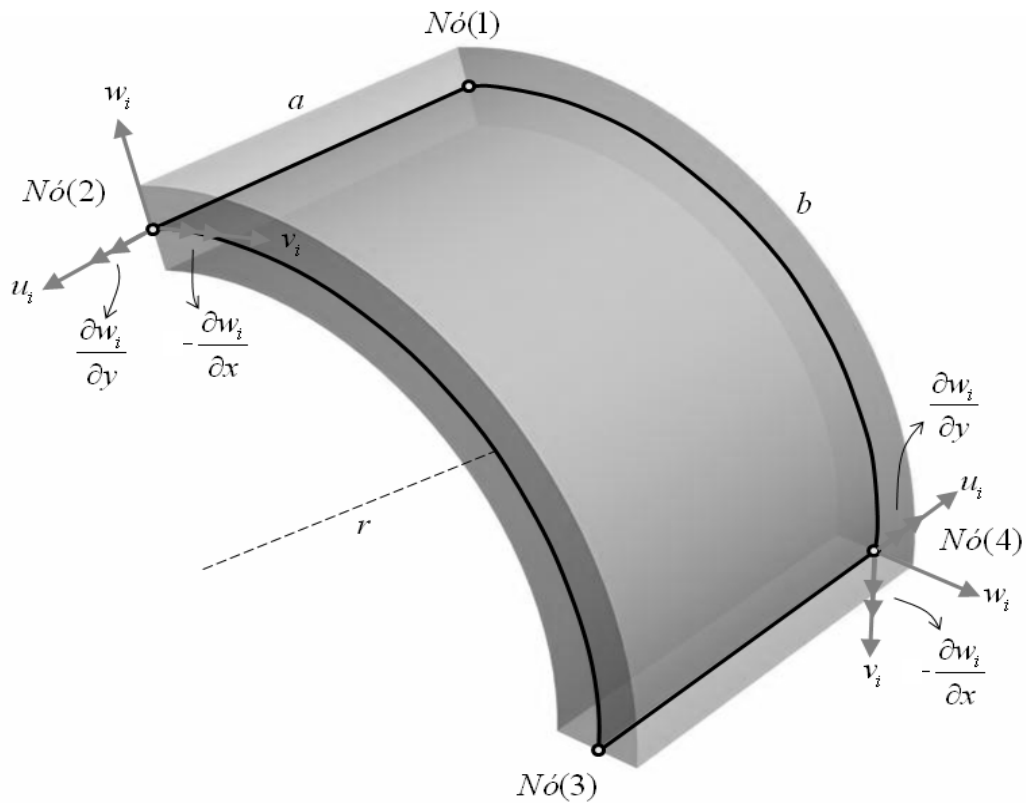


Fig. 1 Pipeline finite elements.

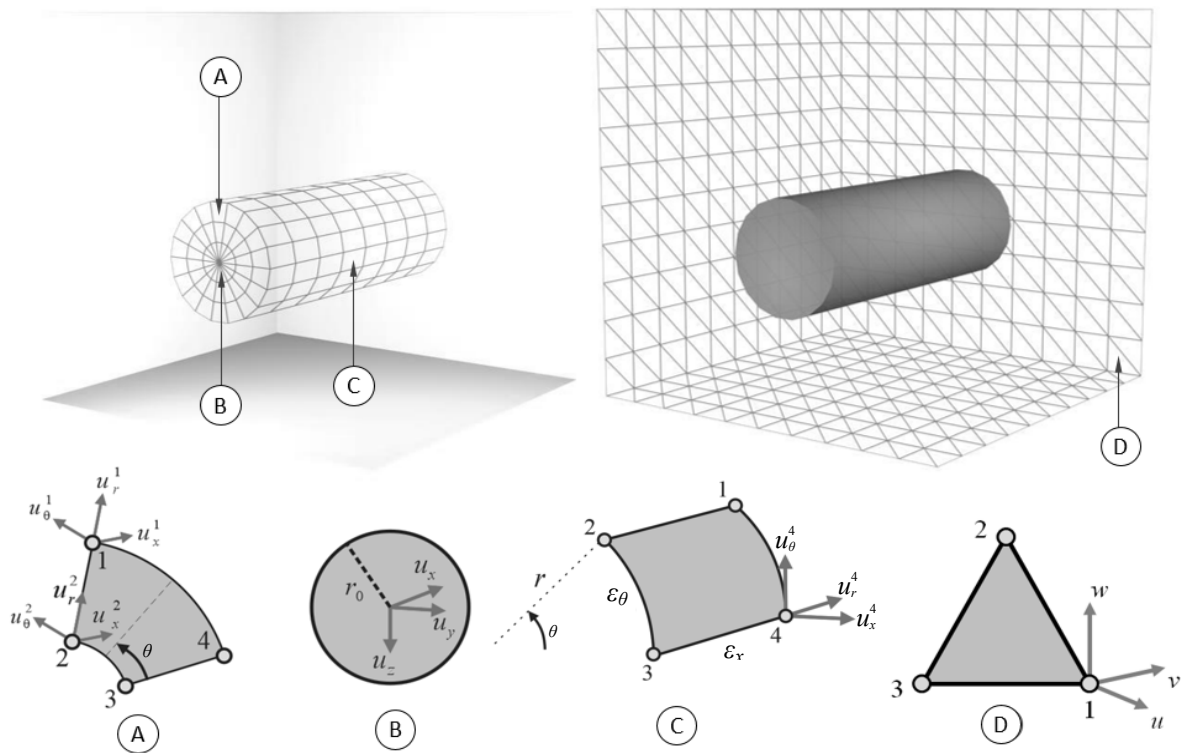


Fig. 2 Especial boundary elements used for soil description.

model, friendly. AutoCAD software is an established worldwide tool in the development of projects of engineering and architecture. It is a great ally of professionals in these areas for owning a complete set of resources, which facilitates the execution of the work and gives them quality and organization in the creation and archive filing. To extend the facilities of the AutoCAD program, it is possible that the users write auxiliary functions, automating tasks and creating new environments to use the software. These functions interact with the AutoCAD program, improving the efficiency of project development. The AutoCAD has a menu of functions (A in Fig. 3), several toolbars (B in Fig. 3) with utilities to design, display, dimensioning, layers, colors, and space for drawing (D in Fig. 3).

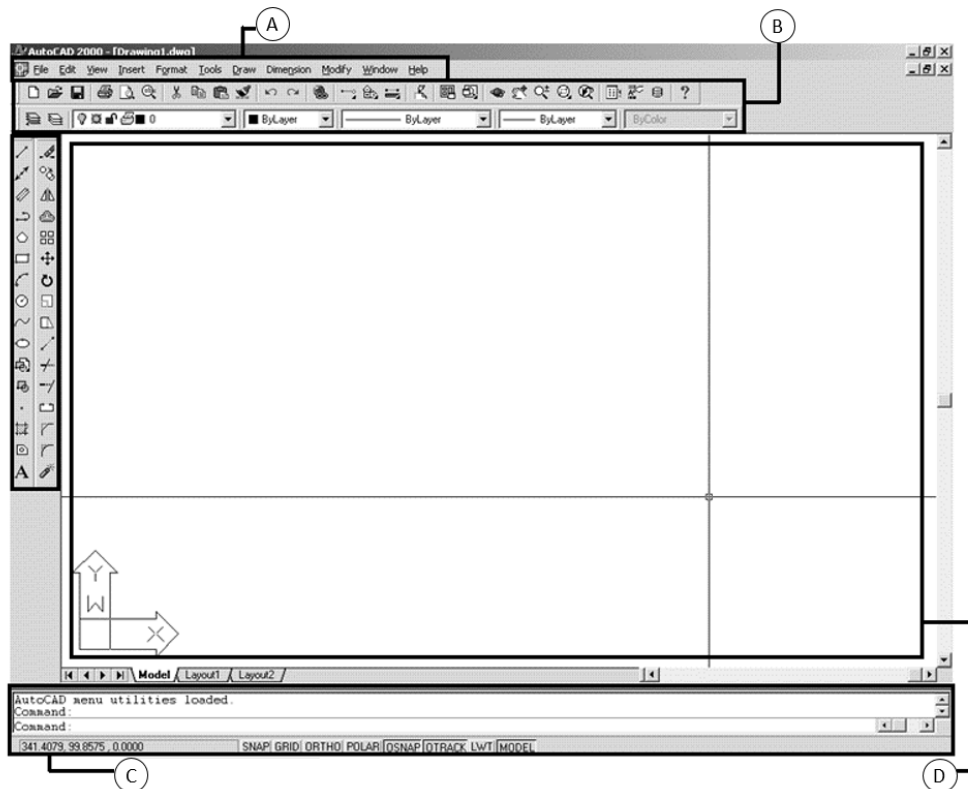
**5. Programming of the Application**

By having an open architecture for customization, AutoCAD makes the development of applications for specific problems possible through the programming

interface API (application program interface) and ObjectARX (AutoCAD runtime extension). An ObjectARX application is a DLL (dynamic link library) written in C++ language, where classes and functions used by AutoCAD are available for deployments. Through the ObjectARX API, derivations by heritage from their native classes can be written, as well as access to database structures and AutoCAD graphics system, and the creation of new commands. Fig. 4 is a description of the contents of the menus for pre-processing (D in Fig. 4), processing (E in Fig. 4) and post-processing (F in Fig. 4) of customized AutoCAD environment.

In Fig. 5, the new interface of AutoCAD is shown, with new menus and windows preview of results that was designed using the ObjectARX API capabilities already described: menu of functions (A in Fig. 5), space for drawing (B in Fig. 5), command prompt (C in Fig. 5) and results dialog (D in Fig. 5).

The basic structure of ARX (AutoCAD runtime extension) module must implement the entry point



**Fig. 3 Original interface of AutoCAD.**

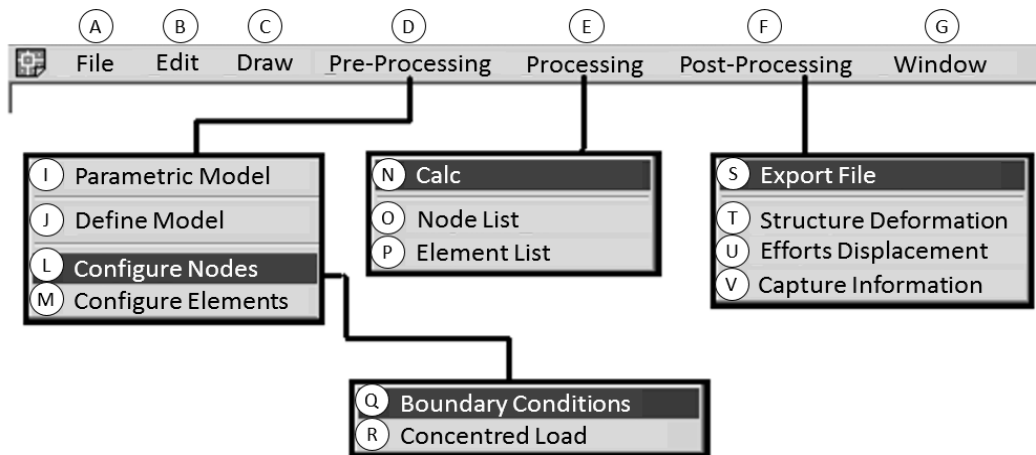


Fig. 4 Menus customized to interface with AutoCAD.

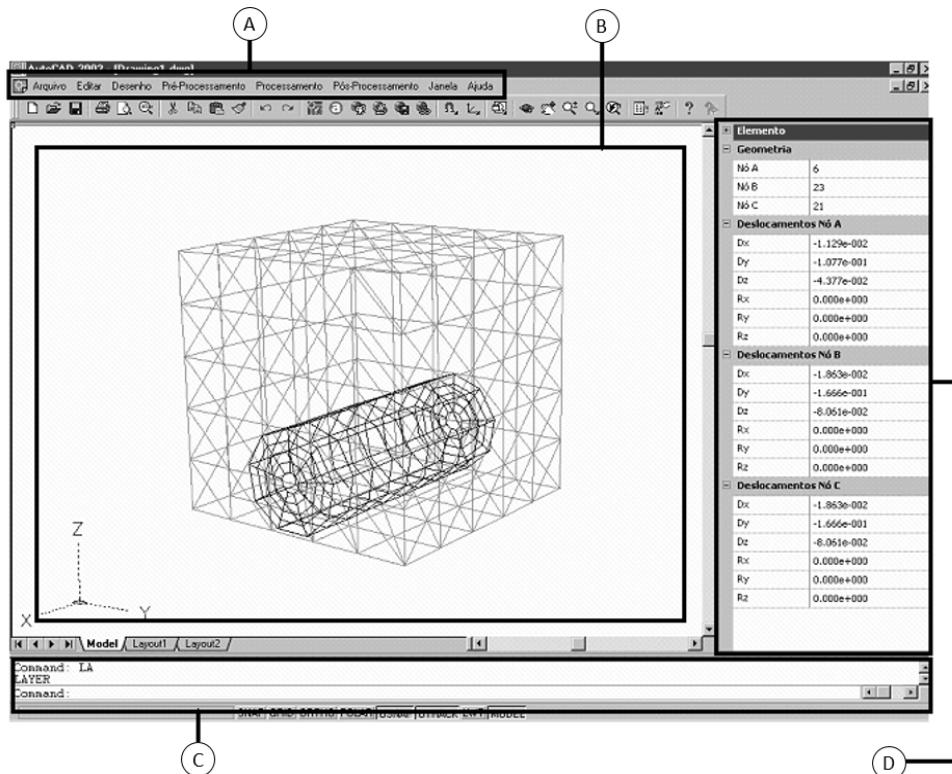


Fig. 5 Modified interface of AutoCAD.

function along with the DllMain function. This function is responsible for effecting communication between AutoCAD and the application that was developed in ObjectARX. The entry point and DllMain functions are shown in Fig. 6.

The new commands are defined through the entry point function. An ARX file can store numerous new commands that are available only after registration. An example registration of commands is shown in

Fig. 7. The new registered commands must have a group, a global name and a local name that are passed as parameters to the method `acedRegCmds > addCommand`.

## 6. Saproms.dll, Saproms.arx and the AutoCAD Software

The saproms.dll library is linked to AutoCAD using saproms.arx. Their use is at the stage where the finite

```

////////////////////////////////////
// DLL Entry Point
extern "C"
BOOL WINAPI DllMain(HINSTANCE hInstance, DWORD dwReason, LPVOID
{
    if (dwReason == DLL_PROCESS_ATTACH)
    {
        // Extension DLL one time initialization
        DCadDLL.AttachInstance(hInstance);
        InitAcUiDLL();
    } else if (dwReason == DLL_PROCESS_DETACH) {
        // Terminate the library before destructors are called
        DCadDLL.DetachInstance();
    }
    return TRUE;    // ok
}

////////////////////////////////////
// ObjectARX EntryPoint
extern "C" AcRx::AppRetCode
acrxEEntryPoint(AcRx::AppMsgCode msg, void* pkt)
{
    switch (msg) {
    case AcRx::kInitAppMsg:
        // Comment out the following line if your
        // application should be locked into memory
        acrxDynamicLinker->unlockApplication(pkt);
        acrxDynamicLinker->registerAppMDIAware(pkt);
        InitApplication();
        break;
    case AcRx::kUnloadAppMsg:
        UnloadApplication();
        break;
    }
    return AcRx::kRetOK;
}

```

Fig. 6 Entry point and DllMain functions.

```

// This functions registers an ARX command.
// It can be used to read the localized command name
// from a string table stored in the resources.
void AddCommand(const char* cmdGroup, const char* cmdInt, const char* cmdLoc,
                const int cmdFlags, const AcRxFunctionPtr cmdProc, const int idLocal)
{
    char cmdLocRes[65];

    // If idLocal is not -1, it's treated as an ID for
    // a string stored in the resources.
    if (idLocal != -1) {
        HMODULE hModule = GetModuleHandle("Saproms.arx");

        // Load strings from the string table and register the command.
        ::LoadString(hModule, idLocal, cmdLocRes, 64);
        acedRegCmds->addCommand(cmdGroup, cmdInt, cmdLocRes, cmdFlags, cmdProc);
    } else
        // idLocal is -1, so the 'hard coded'
        // localized function name is used.
        acedRegCmds->addCommand(cmdGroup, cmdInt, cmdLoc, cmdFlags, cmdProc);
}

```

Fig. 7 Entry point and DllMain functions.

element calculations, the boundary element calculations, the coupling between the elements and solution of the algebraic system that represents the

model are performed. The saproms.dll library is organized into classes of functions described in Fig. 8.

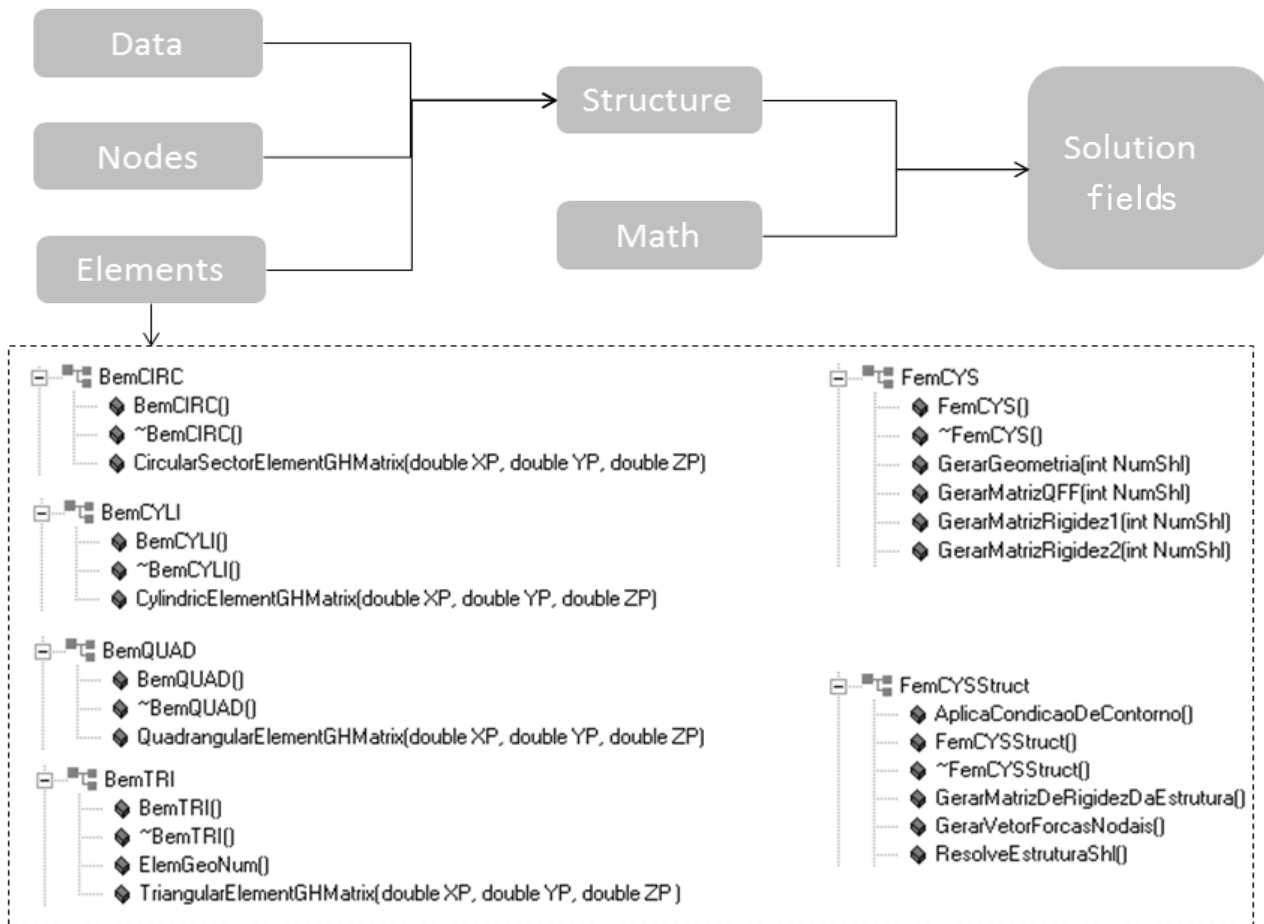


Fig. 8 Classes and functions of the saproms.dll library.

### 7. Parametric Generation of the Model

In AutoCAD environment, discretization can be performed in several ways such as:

- automatic discretization (parametric);
- manual discretization (using drawing functions);
- import geometry from other CAD (computer aided design) applications.

One of the resources developed for the interface allows the construction of parametric problems of soil-pipe interaction. In order to start the discretization, one must access the parametric model in the preprocessing menu (I in Fig. 4). For modeling, values of some fields should be informed. Fig. 9 displays the dialog used to input data and select the type of geometry to be generated (A and B in Fig. 9). It also shows the dialog containing the options for problem

analysis of buried pipelines.

When all fields are filled out and the values chosen are confirmed, the dialog box is automatically closed and the domain is discretized in 3D design environment (Fig. 10).

### 8. Applying the Boundary Conditions and Forces

In Fig. 4 (Q), we observe the pre-processing functions that are used for the discretization step, the application of mechanical properties and the boundary conditions of the model. For the inclusion of boundary conditions, it suffices to set the degrees of freedom existing in the dialog box shown in Fig. 11 (A and B), which is displayed when the user uses the pre-processing function > node sets > boundary conditions.

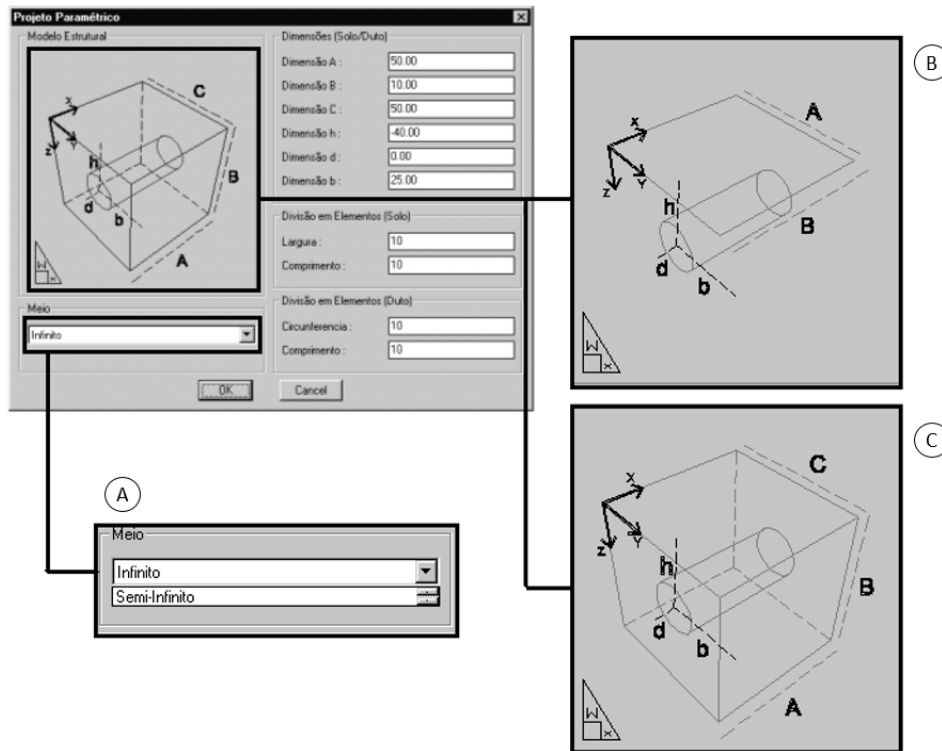


Fig. 9 Parametric modeling function.

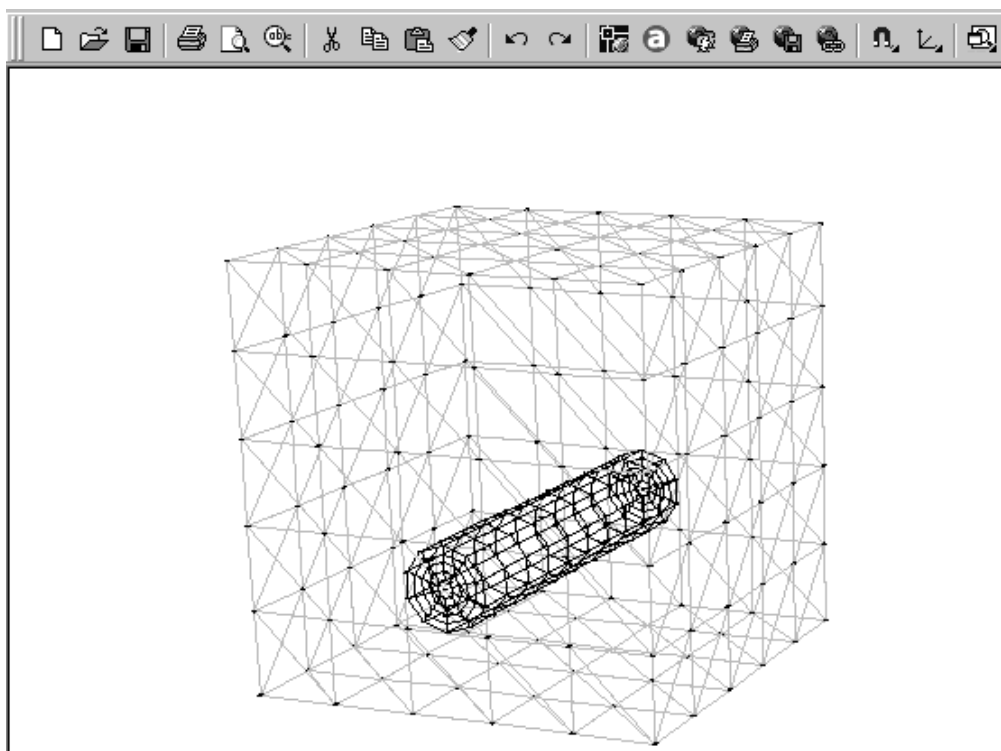


Fig. 10 Parametric modeling of the soil-pipe set.



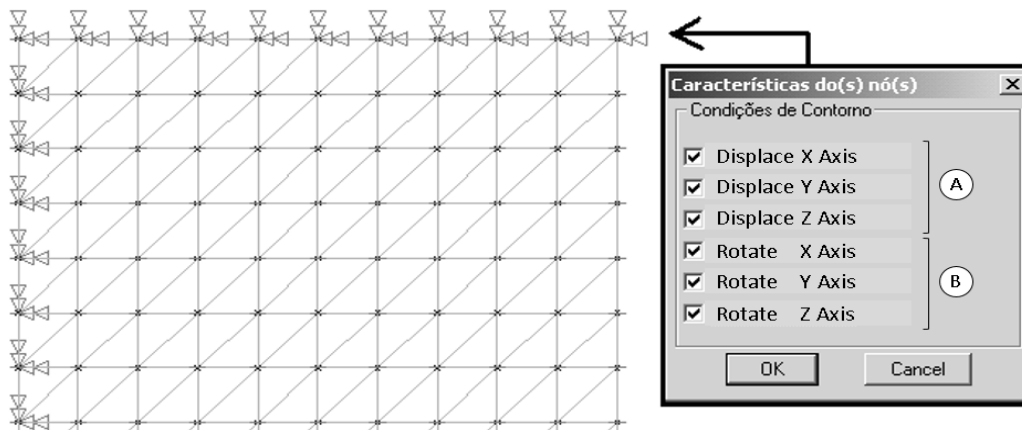


Fig. 11 Boundary conditions in the soil.

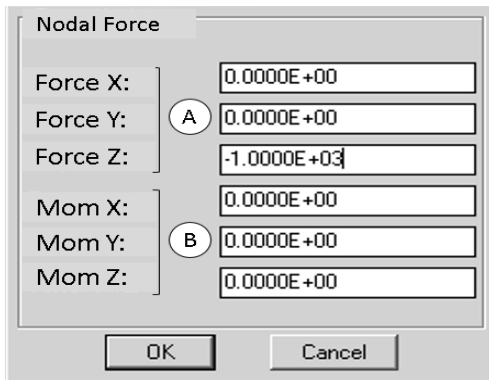


Fig. 12 Dialog of concentrated loads.

In order to apply nodal forces, values should be filled in the dialog box shown in Fig. 12 (A and B), which is accessed through the pre-processing menu > node sets > concentrated loads.

After setting the values in the dialog box that appears and selecting the “OK” button, if the user selects the upper mesh, the loads are displayed as shown in Fig. 13.

### 9. Mechanical Properties

The mechanical properties of the model by their turn are configured through the box shown in Fig. 14 where the required attributions are thickness of the elements (A in Fig. 14), elasticity modulus (B in Fig. 14), Poisson’s ratio (C in Fig. 14) and density (D in Fig. 14).

### 10. Process of Numerical Analysis

The “calculate” function is the most important function of the processing menu, responsible for

initiating the solver function. At this point, AutoCAD gives rise to the present functions in the analysis DLL, transferring all information of the model to be processed to those functions. Fig. 4 (N) shows the functions that include the processing phase. Before starting the calculation process, Fig. 15 shows the dialogue, in which the types of analysis (A, B and C in Fig. 15) can be chosen (in the case of forced vibration, the frequency value is required) through processing > calculate menu.

After selecting the “OK” button, the calculation process is started without the exiting AutoCAD environment. When the process is completed, the values of the fields of displacements can be viewed through the dialog shown in the post-processing menu (Fig. 16), and also, other properties of elements can be verified, for example, connectivity of nodes.

## 11. Results

### 11.1 Analysis of a Cylindrical Solid

In this example, the analysis of a discretized solid (cylinder) is accomplished, as shown in Fig. 17. The cylinder is bound axially in one of its extremities and axially stretched with static load uniformly distributed in another one. The physical and geometric properties of each boundary element are in Table 1.

Fig. 18 illustrates the configuration of the proposed problem: supporting conditions as well as the tractive load which is evenly distributed.

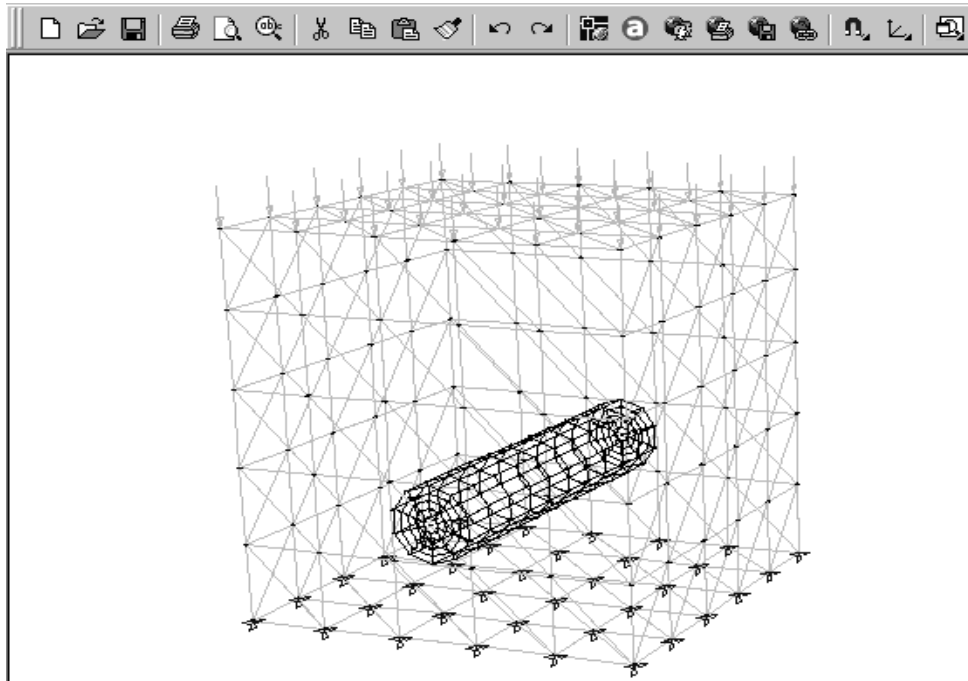


Fig. 13 Loads applied in the soil.

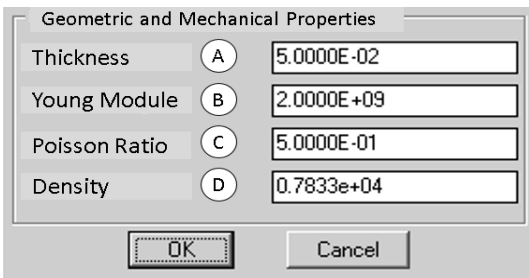


Fig. 14 Properties of elements.

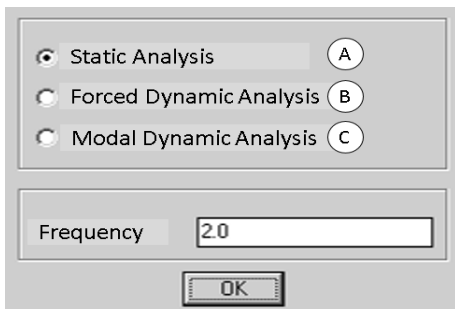


Fig. 15 Processing options.

After processing, the solution of the linear system results in the vector of nodal displacements, shown in Table 2.

The results indicate that the strategy of elements with special geometries of boundary element developed in this thesis is effective.

### 11.2 Analysis of a Shallow Pipe

In this example, a cavity of 2.3 m of radius is in a rock mass whose mechanical properties are exposed in Table 3.

Initially, it was considered a homogeneous pipe and this one was submitted to a confining pressure due to the weight of the rock mass of  $p = 1,000$  kPa, as can be observed in Fig. 18.

In Table 4, the results for the radial displacement at Point 2 of the cavity are observed, which are compared with the analytical solution by Timoshenko [19] and the numerical solution of BEM given by Freitas [20] (using 40 linear boundary elements). These last ones analyze the problem in the plane strain state in order to recover the bidimensional analysis applying the 3D model, it was considered a cavity/cylinder with a length slightly greater than 10 times the diameter of the cavity length, resulting in  $L = 45$  m. Moreover, shifts in the axial extremities of the cavity had been prescribed. The graph in Fig. 19 describes the behavior of the convergence of the results.

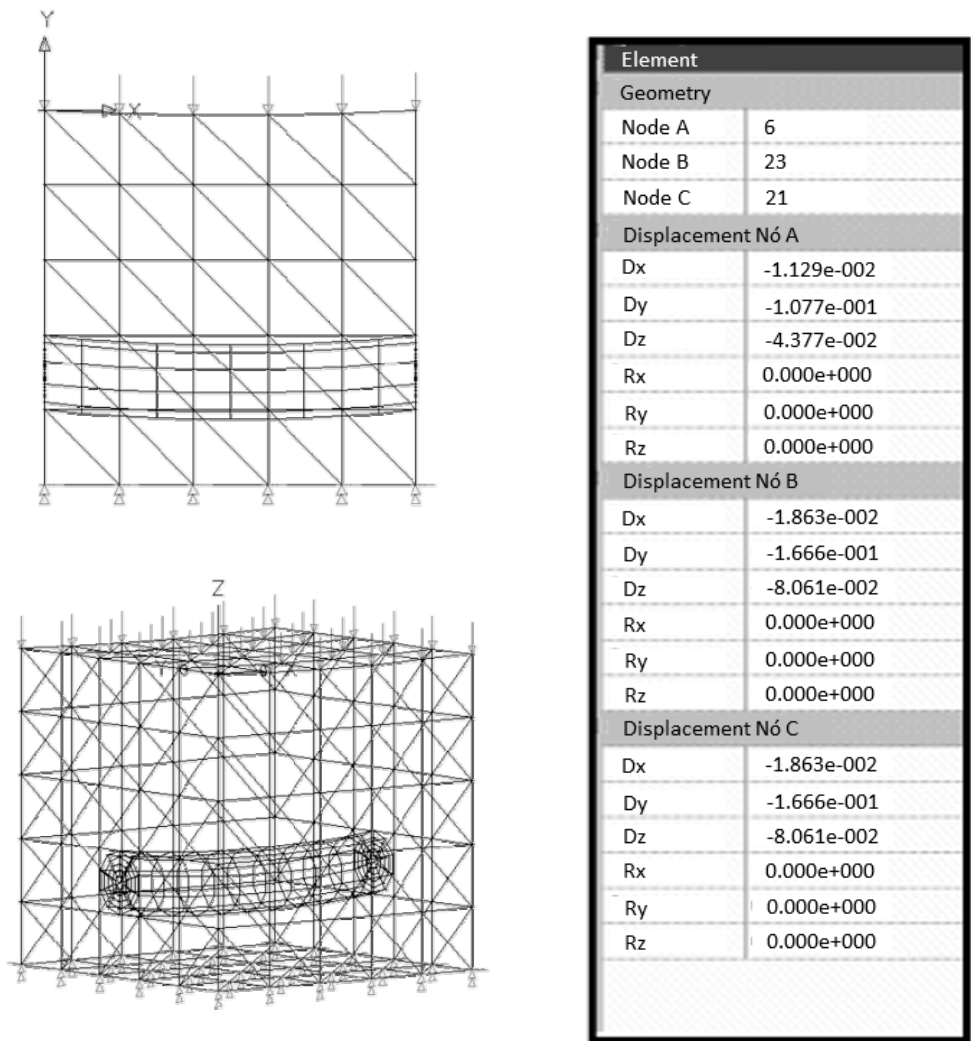


Fig. 16 Results of the structure analysis-displacements.

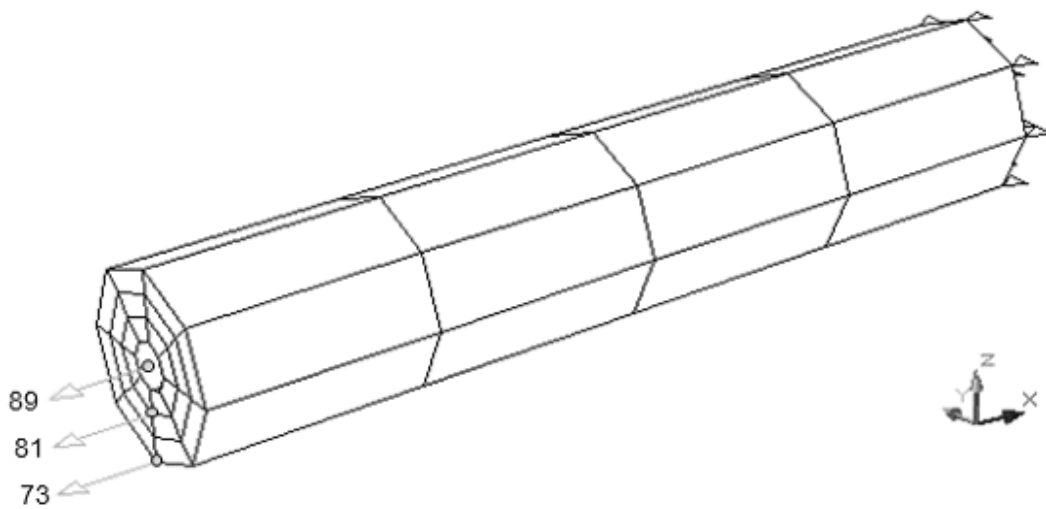


Fig. 17 Solid cylinder.

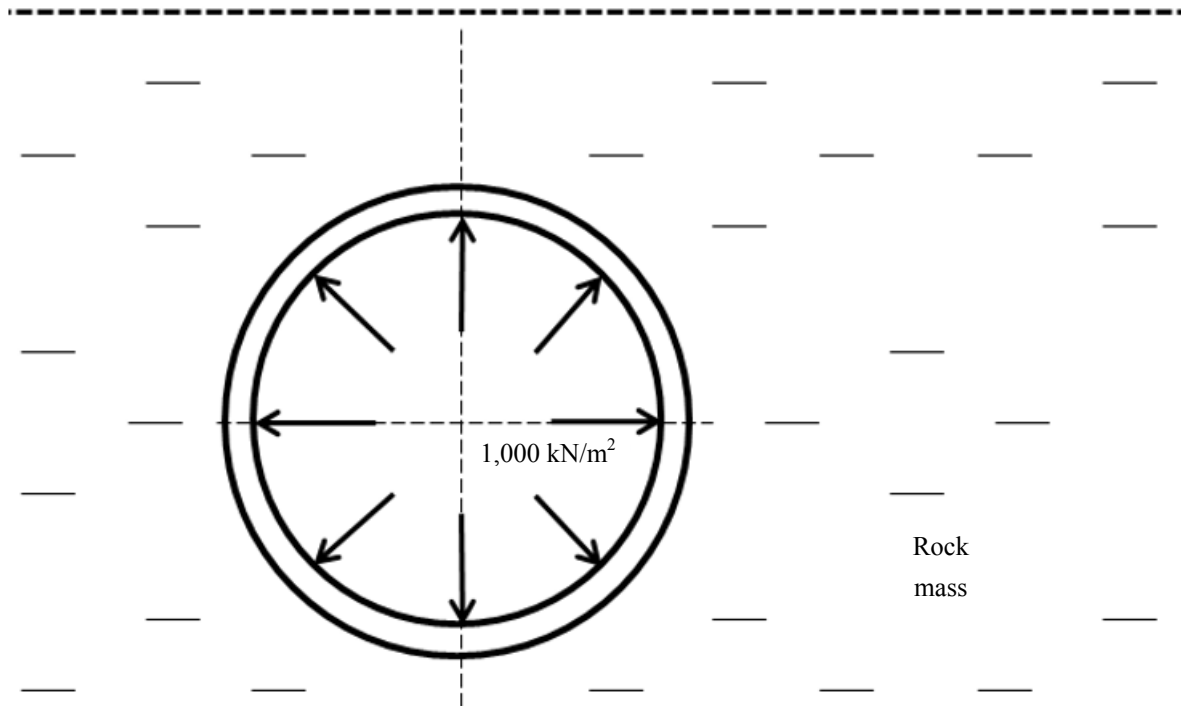


Fig. 18 Pressurized low depth pipe.

Table 1 Model parameters of the analysis of solid cylinder.

Young module $E$ (Pa)	Poisson ratio	Radius (m)	Density (Kg/m <sup>3</sup> )
1.0000e+00	3.0000e-01	8.0000e-01	1.0000e+02

Table 2 Results of the analysis of the solid cylinder (units in m).

Node	X direction	Y direction	Z direction
73	600.0059283e-03	-237.0119402e-12	-12.8353078e-09
81	600.0039539e-03	21.3567404e-09	-12.2432353e-09
89	600.0264948e-03	-52.3799488e-09	-54.8749057e-09

Table 3 Physical properties of soil-pipe coupling.

Elastic module (GPa)	Poisson ratio	Thickness	Structure
12.50	0.20	-	Soil
25.70	0.15	0.3 m	Pipe

Table 4 Results of other authors (radial displacement in m).

Timoshenko [19]	BEM 2D Freitas [20]
153.333e-007	153.000e-007

Table 5 Displacements results (units in m).

Model	1	2	3
Timoshe	-1.5330000e-07	-1.5330000e-07	-1.5330000e-07
BEM 2D	-1.5177922e-07	-1.5280000e-07	-1.5330000e-07
BEM 3D	-1.4804063e-07	-1.5170000e-07	-1.5321640e-07

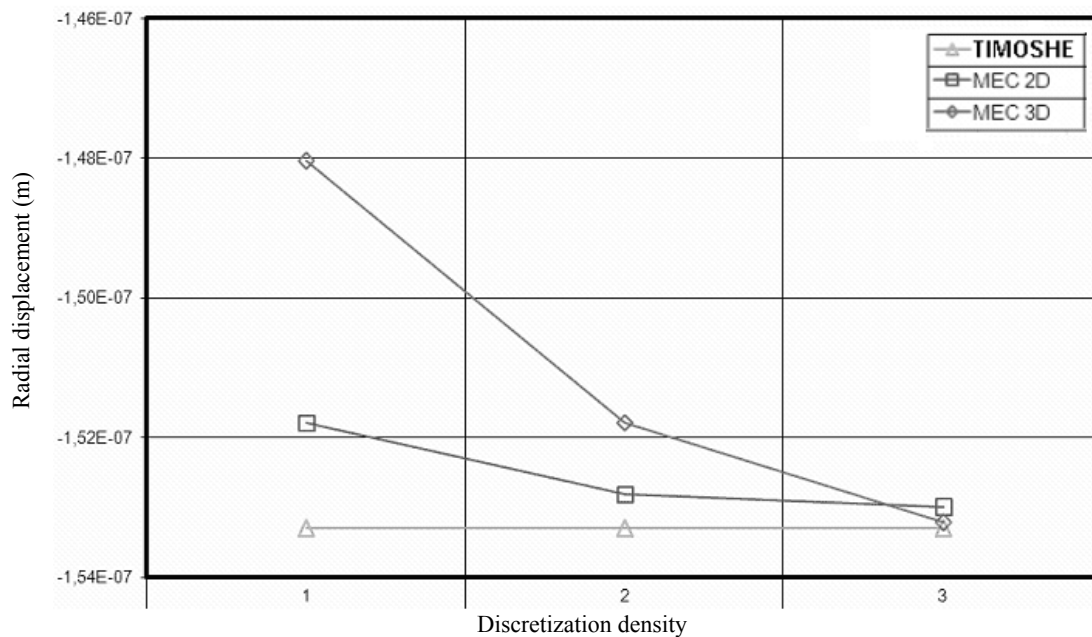


Fig. 19 Displacements results.

The results are presented directly in Table 5.

## 12. Conclusions

In this work, an application in parametric modeling of buried pipe problems in static system, written in C++ using ObjectARX functions, was presented. The app is fully integrated with AutoCAD through saproms.dll and saproms.arx libraries where the stages of pre-processing, processing and post-processing are done in AutoCAD software environment itself. Examples were shown for the certification of models of isolated soil and soil + pipe coupling whose values demonstrate good approximation with results obtained by other authors.

## References

- [1] Aliabadi, M. H., Brebbia, C. A., and Parton, V. Z. 1994. *Static and Dynamic Fracture Mechanics*. Southampton: Computational Mechanics Publications.
- [2] Beskos, D. E. 1987. "Boundary Element Methods in Dynamic Analysis." *Applied Mechanics Reviews* 40: 1-23.
- [3] Biot, M. A. 1937. "Bending of an Infinite Beam on an Elastic Foundation." *Journal of Applied Mechanics, Transactions ASME (American Society of Mechanical Engineers)* 59: A1-A7.
- [4] Brebbia, C. A., and Domínguez, J. 1977. "Boundary Element Methods for Potential Problems." *Applied Mathematical Modelling* 1: 372-8.
- [5] Brebbia, C. A., and Domínguez, J. 1989. *Boundary Elements—An Introductory Course*. London: Computational Mechanics Publications.
- [6] Chen, K. K. 1979. "A Triangular Plate Finite Element for Large Displacement Elastic-Plastic Analysis of Automobile Structural Components." *Computers and Structures* 10: 203-15.
- [7] Djoudi, M. S., and Bahai, H. 2004. "A Cylindrical Strain-Based Shell Element for Vibration Analysis of Shell Structures." *Finite Elements in Analysis and Design* 40: 1947-61.
- [8] Fafart, M., Dhatt, G., and Batoz, J. L. 1989. "A New Discrete Kirchhoff Plate/Shell Element with Procedure." *Computers and Structures* 31: 591-606.
- [9] Flugge, W. 1973. *Stresses in Shells*. 2nd ed.. Germany: Springer-Verlag.
- [10] Greenwood, M. E., and Lang, D. C. 1990. "Vertical Deflection of Buried Flexible Pipes." In *Buried Plastic Pipe Technology*, edited by American Society for Testing and Materials. Philadelphia: ASTM STP 1093.
- [11] Hetenyi, M. 1946. *Beams on Elastic Foundation*. Ann Arbor: University of Michigan Press.
- [12] Hrennikof, A., and Tezcan, S. S. 1966. "Analysis of Cylindrical Shells by the Finite Element Method." Presented at Symposium of Problems of Interdependence of Design and Construction of Large Span Shells for Industrial and Civic Buildings, Leningrad.

- [13] Moser, A. P., and Folkman, S. 2008. *Buried Pipe Design*. 3rd ed.. New York: Mcgraw-Hill.
- [14] Sydenstricker, R. M., and Landau, L. 2000. "A Study of Some Triangular Discrete Reisner-Mindlin Plate and Shell Elements." *Computers and Structures* 78: 21-33.
- [15] Watkins, R. K., and Spangler, M. G. 1958. "Some Characteristics of the Modulus at Passive Resistance of Soil: A Study of Similitude, Highway Research Board." In *Proceedings of the 37th Annual Meeting*, 576-83.
- [16] Watkins, R. K., and Anderson, L. R. 1999. *Structural Mechanics of Buried Pipes*. London: CRC Press.
- [17] Djoudi, M. S., and Bahai, H. 2004. "Strain Based Finite Element for the Vibration of Cylindrical Panels with Openings." *Thin Walled Structures* 42: 575-88.
- [18] Donnell, L. H. 1938. "A Discussion of Thin Shell Theory." In *Proceedings of the Fifth International Congress of Applied Mechanics*, 66-70.
- [19] Timoshenko, S. P., and Woionowsky-Krieger, S. 1959. *Theory of Plates and Shells*. 2nd ed.. New York: Edition MCGraw-Hill.
- [20] Freitas, J. C. A. 2008. "Boundary Element Method Applied to the Analysis of Excavations in Tunnels Using Approximate Dimensional Models." Master dissertation, University of San Paulo.