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Amit Prashant
Ajanta Sachan
Chandrakant S. Desai *Editors*

Advances in Computer Methods and Geomechanics

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Amit Prashant · Ajanta Sachan ·
Chandrakant S. Desai
Editors

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Preface

The Symposium of the International Association for Computer Methods and Advances in Geomechanics (IACMAG) was held at the Indian Institute of Technology Gandhinagar, Gujarat, India, during the period 5–7 March 2019. Computer applications of geomechanics have been gaining much popularity from the early days of the International Conference on Numerical Methods in Geomechanics at Vicksburg in 1972, Blacksburg in 1976 and Innsbruck, Austria, in 1988. It was in that very context the IACMAG was established and it has been growing ever since with various stakeholders contributing significantly from different nations across the world. IACMAG aims at fostering multidisciplinary research and ideas pertaining to geomechanics with particular emphasis on integrating both the practical and the fundamental aspects. The field of geomechanics has evolved with time, and in this regard, IACMAG takes into account the need for judicious simplification of fundamental aspects of geomechanics with a proper amalgamation of theory and experimentation in order that they find their use in practical problems and challenges faced in the industry today.

IACMAG has grown steadfastly in its scope and size encompassing various aspects of constitutive modelling of geomaterials, computational methods and emerging fields of bio-cementation as well as treatment of geomaterials. The Symposium at IIT Gandhinagar aimed at providing a platform for exchanging ideas and recent developments as well as for discussing future visions related to the field of geomechanics and geotechnical engineering. A Pre-Symposium Workshop on “Behaviour of Civil Engineering Materials” was also held in this regard on 4 March 2019 with its focus on the material models commonly used in analysis and design of structures. It also included a hands-on session for implementing simple computer applications of geotechnical engineering for industry and academia. The IACMAG Symposium 2019 included 11 keynote/invited speakers of repute from different backgrounds of the geotechnical engineering community. It involved four parallel sessions with main themes of the symposium being primarily focussed on (i) Geomaterial Behaviour and Material Modelling—including multi-scale modelling, micro-structural instabilities, liquefaction, chemical and bio-effects in geomaterials and field/laboratory testing; (ii) Earthquake Engineering—including dynamics of geomaterials, earth embankments and dams; (iii) Geosynthetics and Ground Improvement with thrust areas on bio-treatment, soft and expansive clays; and (iv) Analysis and Design of Structures—including bridges and foundations as well as soil–structure interaction problems.

We thank all the authors for their contribution to the IACMAG Symposium 2019 that has resulted in the proceedings which is being published in two volumes. IACMAG follows its long-standing tradition in selecting and reviewing these papers with great rigour, and we hope that the proceedings will provide a glimpse of the state-of-the-art practices followed in different fields related to geomechanics and its allied branches. We would also like to express our sincerest of appreciation to the reviewers of the papers and to various technical and financial sponsors for making this event a grand success.

Gandhinagar, India Ajanta Sachan
Gandhinagar, India Amit Prashant
Tucson, AZ, USA Chandrakant S. Desai

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Chandrakant S. Desai is a Regents' Professor (Emeritus) in the Department of Civil and Architectural Engineering and Mechanics at the University of Arizona, Tucson, USA. After completing his MS and PhD from Rice University Houston and University of Texas, Austin in 1966 and 1968 respectively, he joined the U.S. Army Corps of Engineers' Waterways Experiment Station, where he worked till 1974. Subsequently, he joined The University of Arizona, where he has served on various capacities. Prof Desai has authored or edited 23 books and over 345 research papers over the course of his career, which has involved the development and application of constitutive laws with design and fabrication of new and innovative test devices, and of computer methods for solution of a wide range of problems in civil, mechanical and electronics engineering. He has been the founding president of the IACMAG and founding Editor-in-Chief for two international journals in Geomechanics. He has received many awards and distinctions, and is a member of a number of technical societies including an elected Distinguished Member of the American Society of Civil Engineers, USA.

Dynamic Soil–Foundation–Structure Interaction for Bunds in Goa

Leonardo Souza and P. Savoikar

Abstract This paper provides a concise review of Dynamic (Seismic) Soil–Foundation–Structure Interaction (DSFSI) presenting the main methods of DSFSI which are an important and integral part of such studies. The paper spotlights the areas which can use DSFSI including traditional structures like bunds and new structures like pile, pile raft, and mat foundations. Traditional Goan Saraswat Bunds are ancient coconut tree-lined road and flood control embankments found all over Goa which have lasted for thousands of years through storms and earthquakes. Today, as the concept of sustainable construction practices gains growing recognition, they deserved to be studied. The behavior of the tree on top of a bund during earthquakes can be studied using Single-Degree-of-Freedom and vibration damping by pendulum. This paper also presents an equation for the interaction of coconut tree roots as soil springs for their role in damping of the Seismic waves in the bunds. Modeling the bund in MIDAS-GTS-NX showed marginal reduction in acceleration and displacement by the presence of coconut trees.

Keywords Dynamic soil–foundation–structure interaction · DSSI · DSFSI · Soil–structure interaction · DSSI of bunds · Traditional Goan Saraswat Bunds

1 Introduction

Due to increased construction activities along the earthquake-prone zones, Soil–Structure Interaction in its various avatars (Soil–Structure Interaction—SSI, Structure–Soil–Structure Interaction—SSSI, Dynamic Soil–Structure Interaction—DSSI, Dynamic (Seismic) Soil–Foundation–Structure Interaction—DSFSI) has come to prominence. It has been applied to modern structures like High-Rises, Bridges, Harbors, and Nuclear Power Plants and also to traditional historic structures. This paper

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will attempt to analyze if and how it can be applied to Traditional Goan Saraswat Bunds (TGSB), which are historic embankments found in Goa. They are different from other embankments due to the pair of rows of coconut trees planted on top of them.

1.1 Dynamic Soil–Foundation–Structure Interaction (DSFSI)

Dynamic Soil–Foundation–Structure Interaction (DSFSI) studies the interactive relationship between building structures and foundation during earthquakes where the vibrations in one (soil or structure or foundation) cause and/or affect the vibrations in the other.

In analysis of structure, it is erroneously assumed that all structural elements are fixed at the foundation, resisting translation ($F_X = 0$, $F_Y = 0$), settlement ($F_Z = 0$), and rotation ($M_\theta = 0$ or $M_X = 0$, $M_Y = 0$, $M_Z = 0$) (Fig. 1). However in seismic zones, structures get excited by ground shaking caused by earthquake and develop inertial forces. These introduce bending moments and base shears at the interface of structure and foundation. Ignoring these effects can lead to catastrophic response under earthquake loadings. These effects depend on type of structure, foundation, and soil (Fig. 2).

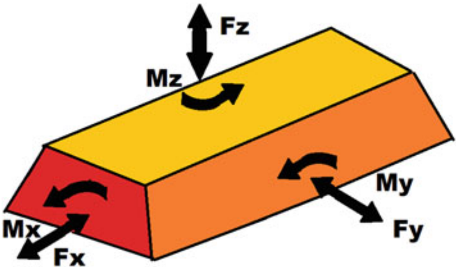


Fig. 1 Forces acting on the foundation during earthquake

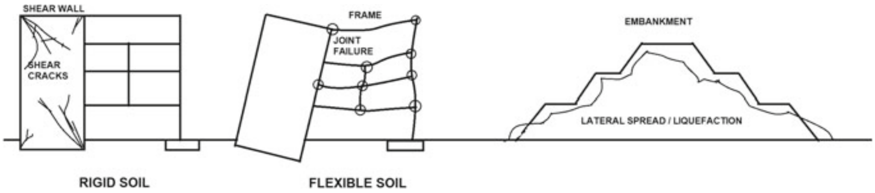


Fig. 2 A structural systems (on rigid soils and flexible soils) and bunds

Hence DSFSI is coupled with problems which links the mathematical relationship between the active and reactive forces along the surface of contact. Both can only be jointly determined. Winkler model, though often used for idealization of soil response due to its simplicity, has the disadvantage of treating soil as a uniform continuum.

2 Literature Review

Sharma et al. [16] conducted a detailed review of the seismic SSI studies associated with building structures by reviewing 110 papers and they concluded that researchers studying SSI articulated diverse views while dealing with the effects of SSI. It describes at length, the origin and developments in the subject of soil–structure interaction. However, from the literature, contradictory opinions were observed about its need, benefits, and demerits. They concluded that Codes provide insufficient procedure on SSI for buildings and their need for improvement. They felt a necessity to examine SSI in detail in order to identify the possible scenarios in seismic SSI by including nonlinearity and ground motion characteristics for both building and soil while evaluating the seismic response of the structure. In current SSI studies, identification of proper parameters to modify ground motion is often ignored. Hence innovative methods that take these into account are needed.

The earliest attempt to analyze DSFSI was initiated in Japan in 1935 by Sezawa and Kanai [15]. They modeled the structure as a thin cylindrical rod with the base as a hemispherical tip fully embedded in a homogeneous half-space. The theory of Dynamic Soil–Structure Interaction (DSSI) was first formulated by Reissner in 1936 [13] through an article. He applied time-harmonic vertical loads to test the behavior of circular disks lying over elastic half-spaces by assuming uniform stress distribution underneath the plates and that the central displacement of the load equals the plate displacement. Hadjian et al. [6] reported the earliest work on Dynamic Soil–Structure Interaction (DSSI). They used the continuum approach in combination with the finite element approach to solve DSSI problems. Kausel [10], Lou et al. [12], Roesset [14] have also documented and extensively reviewed the development of DSSI. They obtained the fundamental analytical solutions for foundations at the surface of an elastic half-space. The conflicting aspects of DSSI were critically appraised, highlighting the existing contradictions. The advantages and disadvantages of the existing standard methods of DSSI analysis, viz., the direct method and sub-structuring method were discussed. Lai and Martineli [11] have beautifully explained the concept and importance of Dynamic Soil–Foundation–Superstructure Interaction analysis when assessing the structural response of shallow and deep foundation typologies in reaction to earthquake loading. Various codes from different countries have given diverse methods of dealing with DSFSI. Eurocode 8, EN 1998-1 [2], states the conditions to consider SSI, however, avoids specific procedures for the technical computation of DSFSI. ASCE 7-05 [1] accommodates DSFSI effects by either adjusting the results obtained from fixed base analysis or by including soil flexibility. IS 1983 [8], the Indian standard for earthquake resistant design, exempts structures supported on rock and rock-like material from the consideration of SSI while avoiding the mention of DSFSI in the procedure for analysis and design of foundations in soils. Both ASCE 7-05 [1] and FEMA (356-2000 [3], 440-2005 [4], 450-2003 [5]), permit reduction of base shear force by taking into consideration damping with a suitably modified time period. The DSSI modeling using various constitutive models and interface nonlinearity is suggested by Japanese code JSCE [9].

There is however inadequate information on DSFSI as applied to trees and their role in vibration damping of dynamic loading. Modeling by conventional software is also not possible as there is no provision to consider the damping effects of tree mass and tree roots.

3 Applications of DSFSI

DSFSI can be widely used for any type of structure combined with any type of foundation. The nature of the ground motion and the surrounding soil cause amplification and de-amplification of the seismic waves governing the unique structural response in DSFSI.

3.1 Modern Structures

Pile Foundation: The nonlinear soil behavior and liquefaction during earthquakes cause an extremely complex seismic response of structures supported on a pile foundation [7, 17, 19]. The DSFSI of soil–pile–structure interaction has been studied widely and is extremely important for its seismic analysis and design.

Bridge Foundation: When a bridge traverses a basin or a valley, it usually needs columns with different lengths. Bridges with varying column lengths have detrimental seismic behavior during earthquake events [19]. A sizeable concentration of seismic forces in the shorter columns (the stiffer parts of the lateral resisting system) causes stiffness irregularities in these type of bridges. Very high shear and moment forces arise in these columns. Eurocode uses a force-based bridge design methodology.

Shallow Foundation: DSFSI has significantly improved the performance of buildings on shallow foundations like mat foundations [7, 17] during many Earthquakes. Comparison of traditional fixed base response, with numerical analyses of buildings on beds of nonlinear springs, has shown a reduction in the forces transferred to structures due to DSSI.

Combined Pile Raft Foundation: The effect of axial load along with seismic forces on combined piled raft foundation system showed appreciable improvement as compared to other foundation systems [17] in layered soil.

Jetty Design: The conventional engineering assumption representing seismic input as vertically polarized shear waves is usually adopted as a starting point in jetty design as these waves are often assumed to be critical. It is an oversimplification, where Rayleigh waves and vertical motions may also affect the jetty's seismic response. Their effect of using DSFSI is a matter for future research.

Nuclear reactors: Nuclear reactors [7, 19] are vital structures that need to properly designed for both earthquake loads and blast loads. DSFSI is critically needed for the design of such structures.

3.2 Historic Structures

There are scarce studies done on DSFSI for historic structures and this is a promising field of research. Many such important structures (Gopurams, minarets, Clock towers, religious structures, palaces, etc.) have survived thousands of years and an attempt must be made to understand why some remained while others fell during earthquake events.

3.3 Traditional Goan Saraswat Bunds

Traditional Goan Saraswat Bunds (TGSB) are long-established road and flood control embankments found all over Goa. They have lasted for thousands of years through storms and earthquakes and even cannon fire [18] with minor annual maintenance. Their heights vary from 1 to 3 m (with few touching 6–9 m). Today, as the concept of sustainable construction practices gains growing recognition, they deserved to be studied. Their behavior during earthquakes can be studied using SDOF and DSFSI as discussed below. This is a subject worthy of further research as it has wide applicability in rural India. The coconut tree can be taken as a structural element causing damping due to inverted pendulum SDOF system, while the roots can be considered as foundation elements with spring damping systems.

4 Kinematic and Inertial Effects of Seismic Waves

Due to the presence of a dynamically excited structure at a soil site, two phenomena known as kinematic and inertial effects occur. Kinematic Interaction represents the seismic input in the absence of the structure sitting at the site. The second phenomenon Inertial Interaction results from the dynamic coupling between a structure and its supporting ground.

The magnitude of kinematic interaction depends on the structural geometry, foundation size, foundation embedment, free-field motion kinematics, and the angle of incidence of the seismic waves (Fig. 3). However, there is no kinematic interaction when a foundation located at ground surface (i.e., a shallow foundation) is hit by a

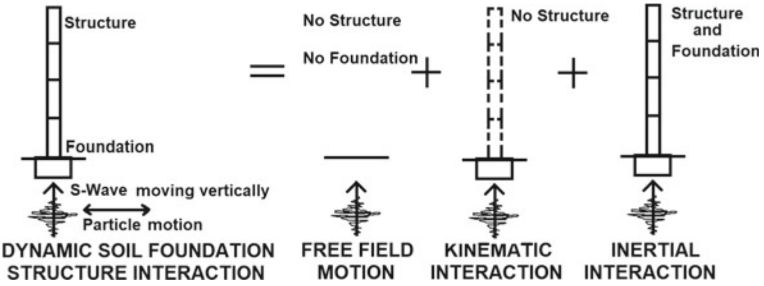


Fig. 3 Kinematic and inertia interaction

vertically propagating S wave. The dynamic response of the foundation is frequency-dependent due to the inertial and dissipative properties of the soil–foundation system. Consider a Single-Degree-Of-Freedom (SDOF) system with a mass M and a spring with flexural stiffness K, which is fixed at the base and subjected to horizontal displacement. It is controlled by M and K (Fig. 4a).

The following relation gives the fundamental period T_{fix} of the system (Eq. 1):

$$T_{fix} = 2\pi/\sqrt{K/M} \tag{1}$$

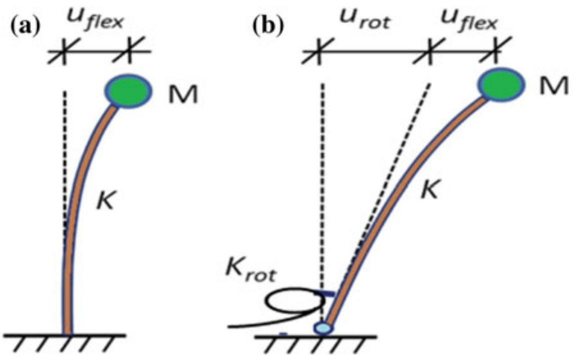
When a rotational spring indicating soil compliance, where the base can rotate, is connected at the base for the above SDOF system, (Fig. 4b) the following pair of equations give the global response of the system (Eqs. 2, 3):

$$F = K_{eq}u = K_{rot}u_{rot} = Ku_{flex} \tag{2}$$

$$u = u_{rot} + u_{flex} \tag{3}$$

where u denotes displacement along x-axis, u_{rot} denotes rotational displacement, u_{flex} is the displacement due to bending, and K_{rot} is the rotational stiffness of the spring,

Fig. 4 SDOF system with **a** fixed base and **b** rotation spring base



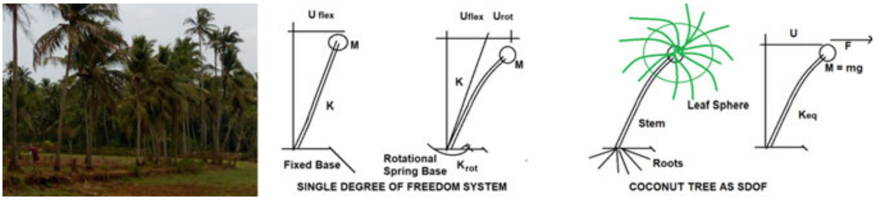


Fig. 5 Coconut tree as a structural element with root foundation—inverted pendulum damping system

the following relations give the equivalent stiffness (K_{eq}) and the fundamental period (T_{eq}) of the system (Eqs. 4, 5):

$$K_{eq} = 1/\left(\frac{1}{K} + \frac{1}{K_{rot}}\right) \tag{4}$$

$$T_{eq} = 2\pi/\sqrt{K_{eq}/M} \tag{5}$$

Thus, it can be seen that the SSI effect augments the natural period of the structure. This concept is easily applicable to Coconut trees placed on bunds (Fig. 5).

5 Methods of Analyses

The traditional DSFSI analysis methods are direct and indirect (substructure) approaches. The macroelement concept is a comparatively new and innovative approach in geotechnical engineering to solve DSFSI problems that combines the merits of the direct and indirect approaches without their shortcomings.

5.1 *Direct Approach*

This approach is conceptually easy but computationally difficult. The structure and the soil volume are both a part of the same model (Fig. 6). Using one of several numerical discretization techniques (e.g., Finite Element Method, Spectral Element Method, and Finite Difference Method), this can be analyzed in a single step. Soil nearer the foundation can be discretized into smaller elements for greater accuracy. The zone of fine discretization may extend to twice base width at discretion of designer and the nodes in figure represent the points where the interaction takes place. The Eq. (6) of motion is given by

$$\text{ű}_{total}M_{total} + u_{total}K \quad = -M_{total}\text{ű}_{base} \tag{6}$$

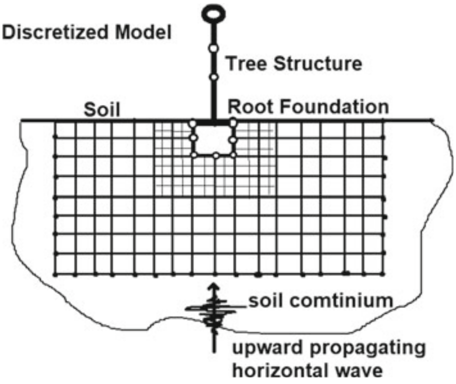


Fig. 6 Model for direct approach for coconut tree

where $\ddot{u}_{base}$ represents the input motion applied at the base of the model, M_{total}, K $\ddot{u}_{total}$, and u_{total} are the mass and stiffness matrix of the global system and the acceleration and displacement vectors of the system, respectively.

5.2 Substructure Approach

This approach is conceptually difficult but computationally easier (Fig. 7). By splitting the superstructure–foundation–soil system into two subsystems (kinematic interaction and inertial interaction) whose response is determined independently, the DSFSI problem is solved.

The seismic response of the superstructure–foundation–soil system is computed using the following three steps:

1. Solve the Kinematic Interaction (KI) problem. Evaluate the change with respect to the free-field ground motion of the seismic wave-field induced by the presence of the foundation. Thus, compute the Foundation Input Motion (FIM)
2. Calculate the frequency-dependent, Dynamic Impedance Matrix (DIM) which represents the dynamic response of the soil–foundation subsystem detached from

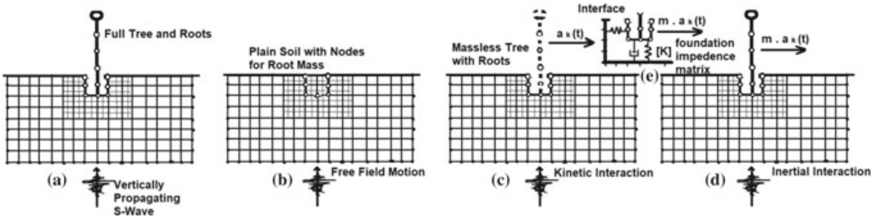


Fig. 7 DSSI using the substructure approach. **a** Geometry of SSI problem; Splitting of the problem into **b** free-field motion, **c** kinematic response, and **d** inertial response; **e** spring dashpot connection of soil and foundation for the transfer of waves

the superstructure. The DIM is complex-valued and generally fully populated due to the coupling between the three translational and three rotational (six) degrees-of-freedom of the foundation.

3. Calculate the dynamic response of the whole system (superstructure, foundation, and surrounding soil) subjected to the FIM (step 1 above) by connecting the finite element model of the superstructure with the foundation–soil subsystem through DIM (step 2 above). Consider Inertial Interaction in this step. Response Spectrum Method (RSM) or the Time-History Method (THM) can be used for the dynamic analysis of the whole system.

The equation of motion (Eq. 7) is given by

$$\ddot{u}_{kin} M_{soil} + u_{kin} K = -M_{soil} \ddot{u}_{base} \tag{7}$$

where $\ddot{u}_{base}$ represents the input motion applied at the base of the model, M_{soil} and K are the mass and stiffness matrix of the global system, u_{kinl} is the kinematic displacement vector that gives the FIM. This is then substituted in the equation for the global system.

5.3 Macroelements Approach

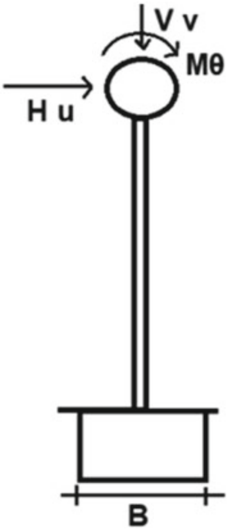
The assumption of linearity of the overall soil-structural system is a severe limitation of the substructure approach. These nonlinearities in DSFSI may arise in different ways, (nonlinear constitutive behavior of structural materials, geometrical nonlinearity along the soil–structure interfaces, and soil nonlinearity in hydromechanical response). These effects can considerably impact the overall structural response under both static and dynamic loadings. The macroelement gives proper foundation response under any loading (horizontal, vertical, and rotational) (Fig. 8). In the macroelement approach for strip foundations, a set of generalized force and displacement vectors $\bar{Q}$ and $\bar{q}$ is usually written in dimensionless form (Eqs. 8, 9, 10) as follows:

$$\bar{Q} = \begin{bmatrix} \xi \\ h \\ m \end{bmatrix} = \frac{1}{v_{\max}} \begin{bmatrix} V \\ H \\ M/B \end{bmatrix} \tag{8}$$

$$\bar{q} = \begin{bmatrix} \eta \\ \varepsilon \\ \zeta \end{bmatrix} = \frac{1}{B} \begin{bmatrix} v \\ u \\ \theta \end{bmatrix} \tag{9}$$

$$\bar{Q} = C_{ep} \bar{q} \tag{10}$$

Fig. 8 DSSI using macroelements approach



A generalized non dimensional stiffness matrix C_{ep} is used to relate $\overline{Ϙ}$ and $\overline{ϙ}$

Where $V_{\max}$, V, H, and M is the maximum normal force, vertical force, the horizontal force, and the moment, respectively, and v, u, and θ is the vertical, horizontal, and rotation displacement, respectively.

5.4 Computer Aided Design

The main feature of DSFSI is the calculation of the force–displacement relationship at the nodes along the soil–structure interface. For DSFSI, the vastness of the complexities involved mandates a computerized analysis. Many commercially available software like ADINA, DYNA4, MIDAS, GEOSTUDIO, OPTUM G2, PLAXIS, etc., are available for such analysis. By using these software, the displacement of each node of the soil–structure interface can be easily computed by assuming a linear soil response with rigid and massless foundation.

6 DSFSI of Bunds

6.1 Damping from Coconut Tree

Coconut trees are placed in uniformly spaced rows on the top of TGSB's. They have a narrow stem of uniform diameter of 250 mm and a height of 5–15 m. The whole mass of leaves and nuts is modeled as a spherical mass 3 m diameter (the actual leaf length is 3–5 m, but the mass is taken as concentrated in middle third) placed on weightless rod and acts as a synchronized inverted pendulum damper. The equations of damped motion (Eqs. 11, 12, 13) for oscillation of tree are given below.

$$\ddot{\theta} + \frac{c}{ml}\dot{\mathrm{O}} + \frac{g}{l}\sin\theta = \frac{\tau_c}{ml^2} \tag{11}$$

It can also be written as

$$\ddot{\theta} + \frac{c}{ml}\dot{\mathrm{O}} + \frac{g}{l}\sin\theta = F\sin(2\pi f\,T_o) \tag{12}$$

$$T_o = 2\pi\sqrt{\frac{l}{g}} \tag{13}$$

where θ is the angular position of the pendulum mass, l is length of massless rod (arm), m is the mass of pendulum, c is the linear damping coefficient, τ_c is the input torque causing motion, g is acceleration due to gravity, F is the forcing amplitude, f is the frequency of motion, and T_o is the period.

6.2 *Damping from Coconut Roots*

On excavation around coconut trees fibrous root system, it was found that every root has average diameter of 7 to ±3 mm and a length of 5–10 m. Coconut roots have reasonably high elasticity and frictional resistance with soil. They can hence be modeled as a collective spring-damper system (Fig. 9).

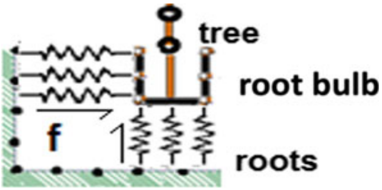
The equations of damped motion (Eqs. 14, 15, 16) of roots are given below.

$$\overset{''}{\mathrm{u}} + 2\zeta\omega_o\mathring{\mathrm{u}} + \omega_o^2 u - 2f_r\mathring{\mathrm{u}} = 0 \tag{14}$$

$$natural\,frequency\,in\,radians = \omega_o = \sqrt{\frac{k}{m}} \tag{15}$$

$$damping\,ratio = \zeta = \frac{c}{2\sqrt{mk}} \tag{16}$$

Fig. 9 Coconut tree roots as spring dampers



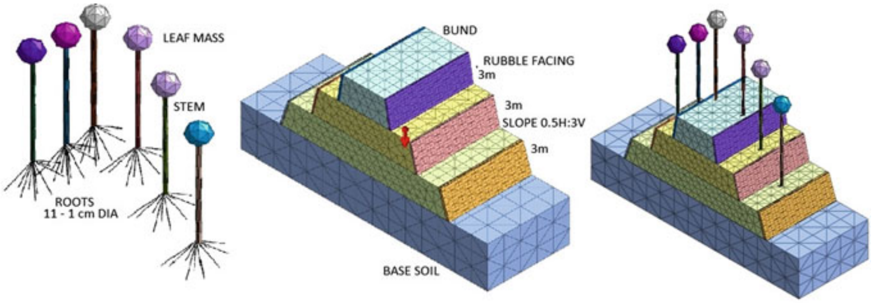


Fig. 10 3D model of bunds Unreinforced/Reinforced by Coconut tree using MIDAS-GTS-NX

where u is the displacement vector, f_r is friction between soil and roots, k is root spring stiffness, m is the mass of roots, and c is the linear damping coefficient.

6.2.1 Computerized SSI of Bunds Using MIDAS

Coconut trees were modeled as lumped masses with 11 single mesh embedded beam element (fibrous root system) 5 m long and treetop as sphere 3 m dia on 10 m 30 cm diameter stem (Fig. 10), with bunds of 3 benching layers of side-slope 0.5 H: 3 V using MIDAS-GTS-NX software. The small size of roots makes it impossible for finer modeling. (Larger number of roots refused to mesh.) The bund was modeled with 1 m mesh and the subsoil 2 m mesh. MIDAS offers auto connect to connect all mesh elements. Releasing M_z at the base of stem allows for rotational spring effect. An earthquake load was taken from MIDAS library of Type III as it closely represents Goa Region and the acceleration and horizontal displacement for reinforced and unreinforced bunds were calculated for linear dynamic loading considering only self-weight. It was not possible to effectively model the roots as springs and trees as pendulum damping masses, as most software are primarily designed for soil and structures.

The tree was modeled as Isotropic Elastic material as it only carried tensile and bending stresses, while the soils were modeled as Isotropic Mohr–Coulomb material as dynamic loading was used. Soil and roots were tested at Goa Engineering college labs and results are given in Table 1.

Table 1 Properties of materials used in MIDAS for computation

Materials	E kN/m^2	1/m	e_o	γ kN/m^3	c kN/m^2	ϕ °	K_o	Damping factor	Type
TREE	8000	0.3	0.65	20			1	0.2	Elastic
RUBBLE	4E4	0.3	0.65	22	150	40	0.30	0.3	Mohr–Coulomb
BUND	1.2E4	0.3	0.5	16.8	18	30	0.52	0.25	Mohr–Coulomb
BASE SOIL	1.2E4	0.33	0.55	19.5	12	38	0.38	0.25	MC

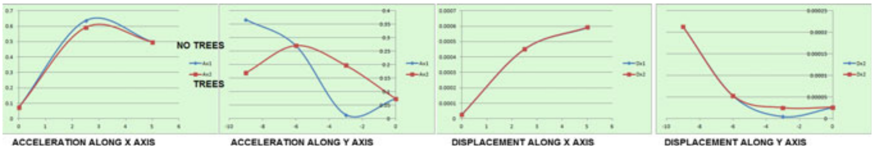


Fig. 11 Acceleration and displacement on bunds with coconut trees (red) and without (blue)—at 0, 2.5, 5 m along width and 0, −3, −6, −9 along depth of bund in Global x-direction

6.3 Results and Discussions

The results (Fig. 11 and Table 2) showed marginal improvement of acceleration 0.0039 m/s^2 and displacement of 0.000001 m near tree offset by diminishing effect away from the tree.

It is also seen that the modeling of fibrous roots as individual elements did not give expected results so there is a need to model them differently (perhaps as a separate soil layer with increased shear strength and damping constant).

7 Conclusions

It is vital to evaluate the effects of DSFSI on structures in a modern development scenario. DSFSI can be used to study new and traditional structures like TGSB's of Goa. As the DSFSI analytical calculations are complex, computer software is preferred. On using MIDAS-GTX-NX software, the presence of single coconut trees has shown marginal reduction in earthquake damage of acceleration 0.0039 m/s^2 and displacement of 0.000001 m near tree, especially in Goa. This is because the present computer-based analysis programs don't model trees and root elements. There is a need to develop software programs to model trees for DSFSI as they provide good damping in case of earthquakes. Modeling a tree as a pendulum and roots as spring dampers is an effective way to deal with the situation. There is scope for further refinement in the modeling process as fibrous roots can't be effectively modeled as individual elements but may need to be modeled as a modified soil layer. An extended model study with rows of coconut trees needs to be done.

Table 2 Variation of acceleration and displacement away from the center (tree)

X Fig no	Without trees		With coconut trees		Y	Without trees		With coconut trees	
	Ax(11c)	Dx(11d)	Ax(11a)	Dx(11b)		Ax(11c)	Dx(11d)	Ax(11a)	Dx(11b)
0	0.07429	0.000027	0.0739	0.000026	0	0.074291	0.000026	0.07397	0.000026
2.5	0.63474	0.000451	0.5928	0.000451	−3	0.014979	0.000005	0.19779	0.000025
5	0.49751	0.000590	0.4991	0.000593	−6	0.27091	0.000053	0.27091	0.000053
					−9	0.36704	0.000213	0.1703	0.000213
Acceleration in x-direction = Ax m/sec^2				Displacement in x-direction = Dx m					