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Silent Boundary Scheme and Analysis of Existing Methods of providing Silent Boundary

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Abstract

For dynamic analysis, it is required to provide viscous boundaries in PLAXIS to reduce the boundary effects and to prevent the reflection of waves from boundaries. So, a study has been carried out to compare the various methods of providing silent boundaries and to see the effectiveness of viscous boundaries used in PLAXIS. In this work, three methods of providing silent boundaries, which are viscous boundaries, local damping, and extended boundary, are analyzed using a 2D finite element program in FORTRAN by considering the simple problem of a two-dimensional vertical bar. Parameters, such as, normal stress at the bottom, vertical displacement at the top, potential energy, kinetic energy, strain energy, and total energy of bar are determined with and without using the above three methods of providing silent boundaries. Results are compared using graphs. It was observed that standard viscous boundaries are not much effective for static analysis but most effective for dynamic analysis.

Keywords: Extended boundary, Local damping, Silent boundaries, Viscous boundaries.

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Introduction

In many problems of engineering and physics, semi-infinite domains exist. However, every numerical model must be terminated at some finite boundary. In numerical simulations of problems involving wave propagation, the use of finite boundaries leads to a reflection of waves upon reaching the boundaries of the mesh. These reflected waves get superimposed with progressing waves and distort the computed results. This problem can be solved by placing the boundary at a larger distance, but this requires the introduction of a large number of elements to model regions, and take more memory and time for computation. In addition, for computational efficiency, it is desirable to place the boundary as close as possible to the finite structure. Thus, there is a need to create a boundary, which is perfectly radiating to outgoing waves and transparent to incoming waves, this boundary is called silent boundary. Silent boundaries are also called absorbing boundaries or transmitting boundaries or non-reflecting boundaries.

There are various methods developed by many researchers which are adopted for providing silent boundaries. Al-Kafaji (2013) introduced a damping factor to damp out the energy of incident wave and damping force is proportional to the out of balance force, for any degree of freedom in the considered system.[1] Kellezi (2000) proposed a cone boundary for transient analysis. This boundary condition includes both a dashpot and a spring to simulate infinite boundary condition.[2] Kim (2012) performed a study to improve the capacity of viscous boundary conditions using dashpots. It was found that using the concept of energy ratio between the transmitted energy of reflected and incident wave the efficiency of viscous boundary condition can be improved for an arbitrary angle of incidence and materials.[3] Kim (2014) investigated the validity of the silent boundary conditions proposed by two researchers. In numerical study, boundaries were modeled as semicircles and as rectangles with dashpots, to examine the absorbing boundaries for waves attacking perpendicularly and having inclined angles of incidence respectively. It was found that absorption ratio was smaller when wave attacking the boundary with an inclination than for the wave perpendicular to the boundary.[4] Li and Xiang Song (2015) proposed a general viscous-spring transmitting boundary for numerical analysis of wave

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propagation in unbounded saturated porous media. It was found that proposed boundary is more efficient and capable of solving dynamic problems in saturated porous media.[5] Liu and Jerry (2003) proposed a gradually damped artificial boundary applied by an exponentially increasing function, to simulate a non-reflecting boundary condition.[6] Lysmer and Kuhlemeyer (1969) proposed a general method through which an infinite system is approximated by a finite system with a special viscous boundary condition by absorbing the striking waves towards the boundary.[7] Ross (2004) presented four typical methods for applying a silent boundary for an infinite domain. These are plane wave approximation (PWA), viscous damping boundary method, perfectly matched layers (PML), and infinite elements. The PWA is a boundary element method ideally suited for fluid media. Viscous damping method is similar to PWA and is used for elastic media. In PML, the boundary layer is made of the same elements as computational domain; however, it has slightly different properties. In the infinite elements, the basic idea is to place element with special shape function to represent the infinite boundary.[8] Shen and Chen (2005) developed a simple silent boundary method for dynamic analysis. By using this method, dynamic deformation could be simulated in a small computational domain.[9] Zienkiewicz (1967) introduced the use of infinite elements. Infinite elements are defined as radiating strips in the exterior regions. The shape functions of such elements include an exponential decay term, so that they mimic the asymptotic behavior at infinity.[10]

Analysis of Existing Methods of Providing Silent Boundary

In this work, following three methods of providing silent boundaries will be analyzed using a 2D finite element program:

Viscous Boundaries

While adopting viscous boundaries, a dashpot is used in place of applying fixities on the boundaries. The dashpot absorbs the increase in stress on the boundary without rebounded. In this work, the use of viscous boundaries will be based on the method proposed by Lysmer and Khulmeyer (1969). The normal and shear stress components absorbed by a damper are represented in Eq. (1) and Eq. (2), respectively.[7] Negative sign shows that these stresses act in the direction opposite to the normal and tangential velocities.

$$\sigma = -a\rho V_p \dot{w} \tag{1}$$

$$\tau = -b\rho V_s \dot{u} \tag{2}$$

Where, σ and τ are the normal and shear stresses, respectively. $\dot{w}$ and $\dot{u}$ are the normal and tangential velocities of the boundary points, respectively.

$$V_p = \text{velocities of P-waves} = \sqrt{\frac{E}{\rho}}$$

$$V_s = \text{velocities of S-waves} = \sqrt{\frac{G}{\rho}}$$

Where, E and G are Young's modulus of elasticity and shear modulus of material, respectively, in which wave propagates, and a and b are dimensionless parameters.

Local Damping

In local damping, a damping factor is introduced to damp out the energy of the incident wave, and damping force is proportional to the out of balance force. For any degree of freedom in the considered system, the local damping can be described as follows by Al-Kafaji (2013)[1]:

$$f^{damp} = -\alpha|f|sign(v) \tag{3}$$

Where,

$$f = f^{ext} - f^{int}$$

and

$$sign(v) = \frac{v}{|v|}$$

In the Eq. (3), f^{damp} acts opposite to the direction of the velocity at the considered degree-of-freedom. The parameter α is a dimensionless damping factor and sign (v) is defined for nonzero values of v.

Extended Boundary

The concept behind this boundary is to introduce a section of elements before the finite element boundary of the finite element model to prevent the reflections of waves. Damping force will be calculated and applied as given in Eq. (3). In this work, this type of extended region is provided in two ways:

- Provide a constant damping factor throughout the extended region.
- Provide a linearly varying damping factor, which is zero at the junction of the extended region and finite element model and maximum on the other side of the extended region.

Analysis with Vertical Bar Problem

The above three methods of providing silent boundaries are analyzed using a 2D finite element program in FORTRAN. To analyze these methods, a simple problem of a two-dimensional vertical bar is considered. The vertical bar of 1-meter length consisting of 50 elements of square size and 102 nodes is taken into account. The bar is restricted against horizontal movement. Hence, velocities and displacements at nodes in the horizontal direction are zero. Stresses and displacements at the bottom and top of the bar are determined in the vertical direction, for different boundary conditions (fixed, free, viscous boundary, and extended region using local damping) and different types of loads. Results are compared using graphs. Properties of the bar are given in Table 1.

Under the Influence of Gravitational Acceleration only

In this case, the bar is subjected to only a gravitational

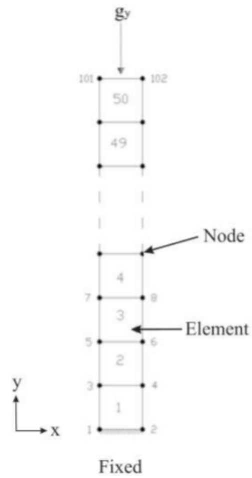

Figure 1: Vertical bar subjected to gravitational acceleration

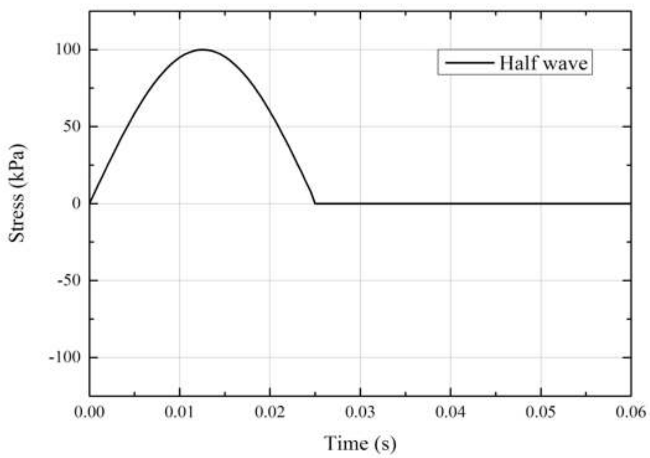

Figure 2: Half sinusoidal stress pulse

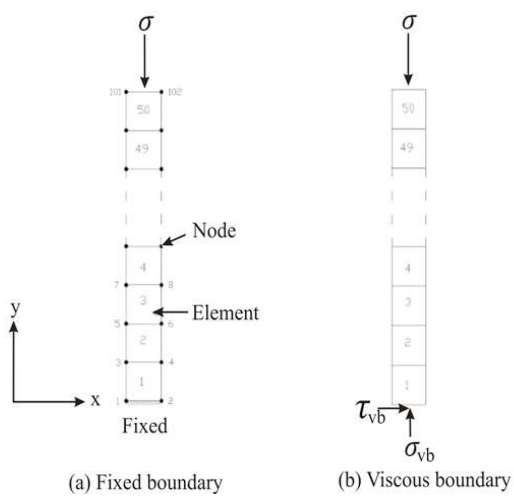

Figure 3: Vertical bar with application of normal vertical stress

Table 1: Properties of bar

Parameter	*Value*
Young's modulus, E (kPa)	1,000
Density of material, ρ (1t/m^3)	1
Cross sectional area, A (m^2)	0.02

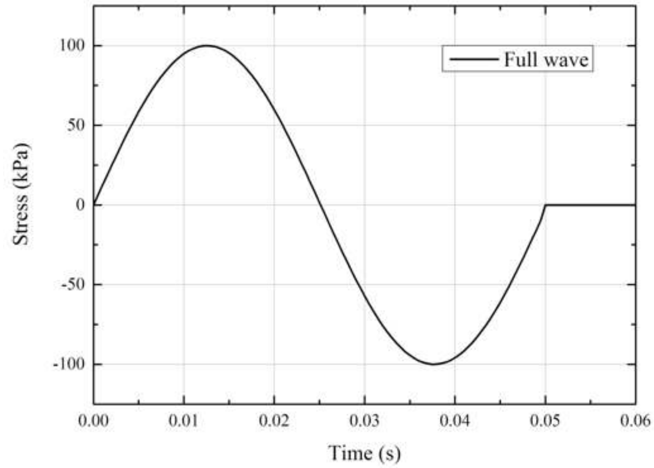

Figure 4: Full sinusoidal stress pulse

acceleration (g_y = -10 m/s^2) in a vertically downward direction, and the bottom of the bar is fixed (Figure 1).

Firstly, normal stress at the fixed bottom, vertical displacement at the top, potential energy, kinetic energy, strain energy, and total energy of the bar are determined without any damping. Then, local damping, as described above, is applied, and again normal stress at the fixed bottom, vertical displacement at the top, and all the energies are determined.

Under the Influence of Half Sinusoidal Stress Wave

In this case, the bar is subjected to only a half sinusoidal stress wave (σ) in a vertically downward direction (Figure 2).

$$\sigma = -100 \sin(125t) \text{ kPa} \quad (4)$$

From the Eq. (4), the frequency of this stress wave is 50 Hz. This force is applied as a pulse for 0.025 seconds in this case. Firstly, with fixed boundary [Figure 3(a)] normal stress at the fixed bottom, potential energy, kinetic energy, strain energy, and total energy of the bar are determined without any damping. Then, viscous boundary condition is applied at the bottom [Figure 3(b)], as described above, and again normal stress at the fixed bottom and all the energies are determined. Then, local damping (α = 0.3) with fixed bottom is applied and all the parameters are determined.

Under the Influence of Full Sinusoidal Stress Wave

In this case, the bar is subjected to only a full sinusoidal stress wave (σ) in a vertically downward direction (Figure 4). Firstly, with fixed boundary normal stress at the fixed bottom, potential energy, kinetic energy, strain energy, and total energy of the bar are determined without any damping. Then, viscous boundary condition is applied at the bottom, as described above, and again normal stress at the fixed bottom, and all the energies are determined. Then, local damping with the fixed bottom is applied, and all the parameters are determined. From the Eq. (4), the frequency of this stress

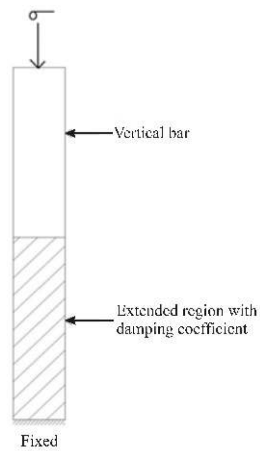

Figure 5: Vertical bar with extended region

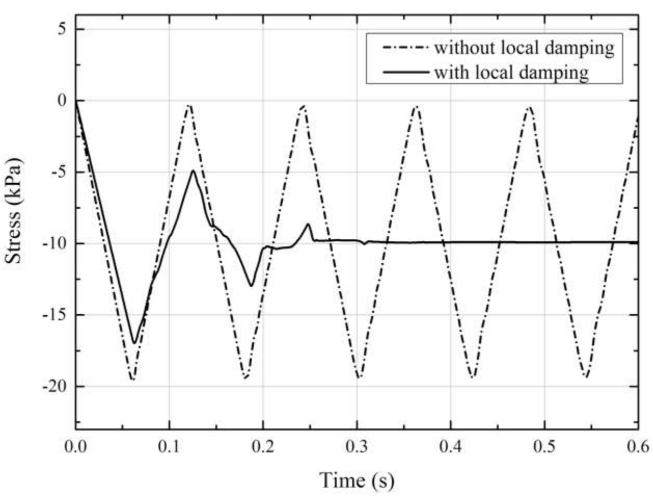

Figure 6: Stress at fixed bottom of bar with gravitational acceleration only

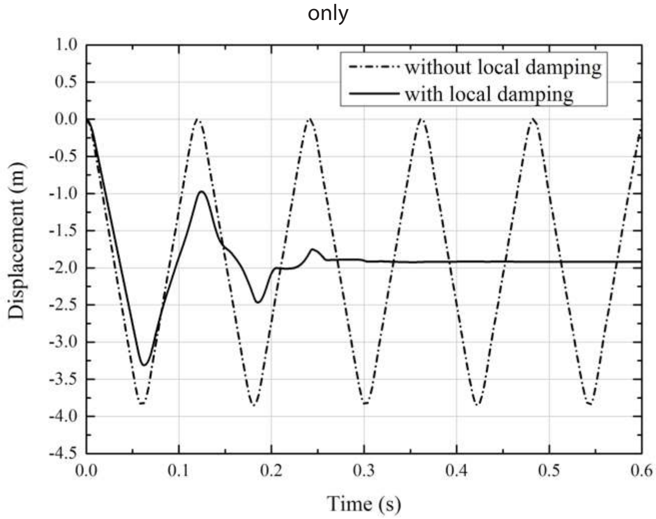

Figure 7: Displacement at the top of bar with gravitational acceleration only

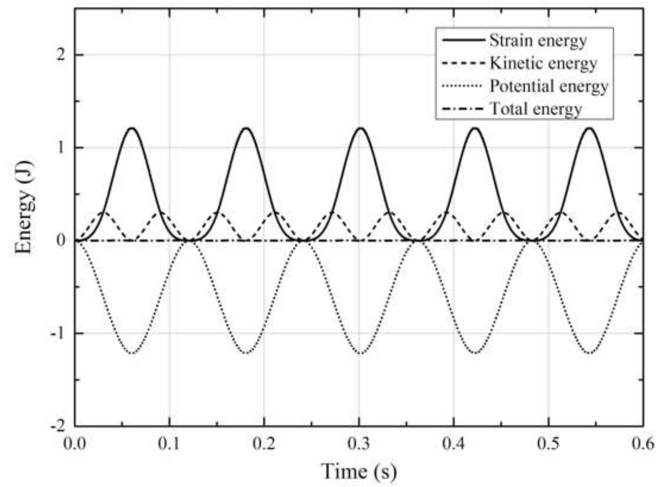

Figure 8: Energy of the bar with gravitational acceleration only, without damping

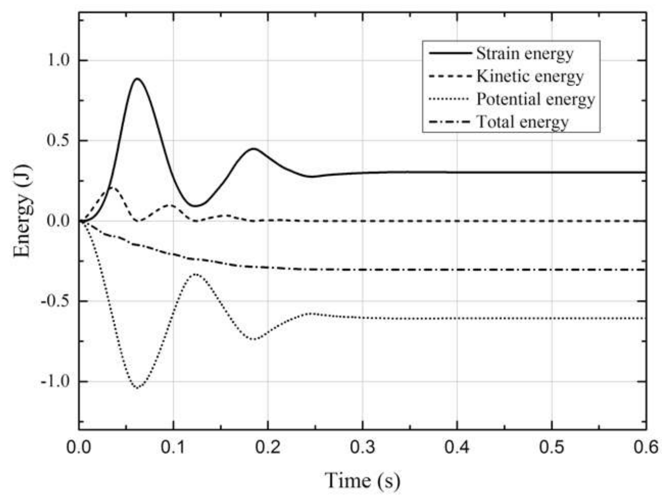

Figure 9: Energy of the bar with gravitational acceleration only, with local damping

wave is 50 Hz. This force is applied as a pulse for 0.05 seconds in this case.

Use of Extended Region as Boundary

In this, an extended region of 1-meter consisting of 50 square elements is added at the bottom of the bar. In this region, a damping factor is provided (Figure 5).

This damping factor is provided in two ways. Firstly, damping factor is provided as constant value through the whole extended region. Secondly, a linearly varying damping factor is provided. Then, a full stress wave as given in Eq. (4) is applied to the bar, and normal stress at the junction of the extended region and vertical bar is determined.

Results and Discussion

All results are compared using graphs.

Under the Influence of Gravitational Acceleration only

Figure 6 shows that with local damping stress wave amplitude at the fixed bottom reduced, damped out, and reached to a constant value.

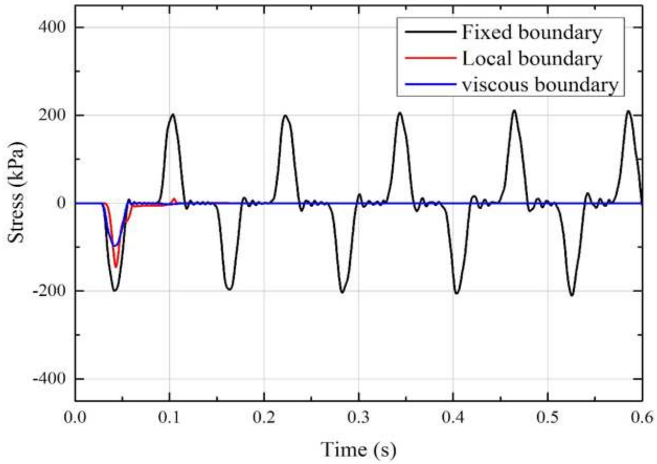

Figure 10: Stress at the bottom of bar with half sinusoidal stress wave pulse

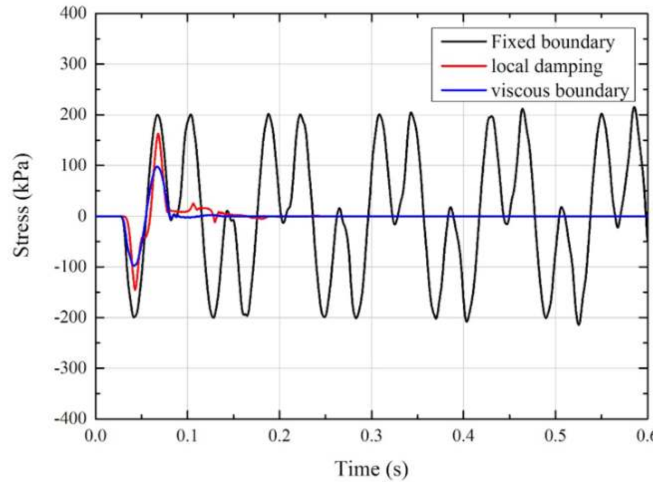

Figure 12: Stress at the bottom of bar with full sinusoidal stress wave pulse

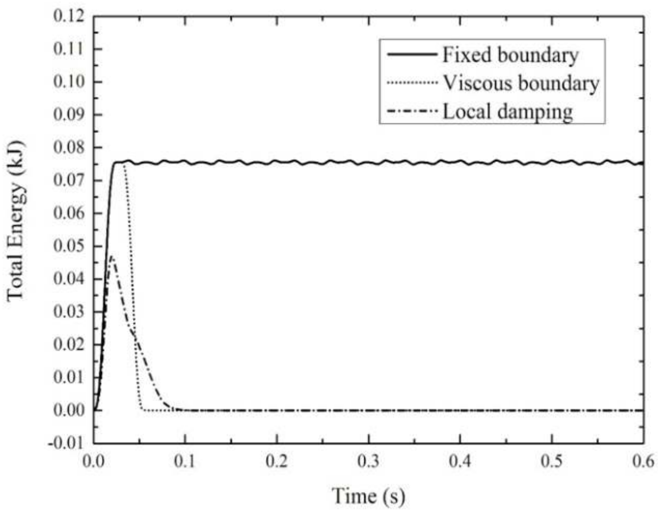

Figure 11: Total energy of the vertical bar with half sinusoidal stress wave pulse

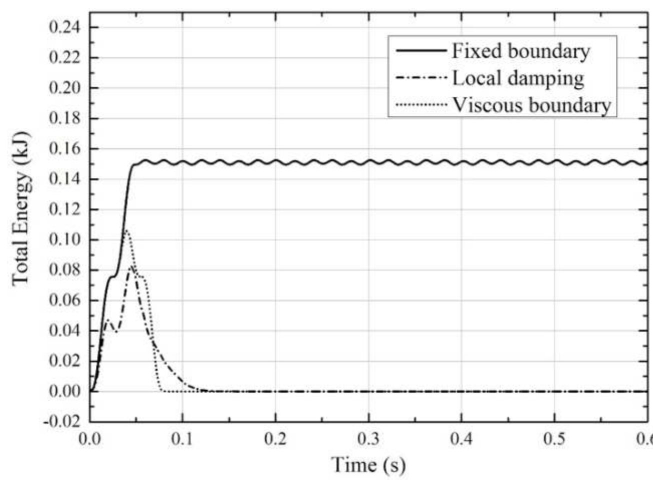

Figure 13: Total energy of the vertical bar with full sinusoidal stress wave pulse

Figure 7 shows that with local damping displacement at the top of the bar reduced, damped out, and reached to a constant static value. Figure 8 shows that total energy of the system is zero because no external force is applied here. Figure 9 shows that due the application of local damping total energy of the system decreases.

Under the Influence of Half Sinusoidal Stress Wave

Figure 10 shows that due to the fixed boundary reflection of stress wave occur with double amplitude, which can be effectively reduced with the application of viscous boundary in place of the fixed boundary. It can also be noticed that the application of local damping also reduced the reflection of waves, but some reflection may occur, which depends on the value of the damping factor.

Figure 11 shows that with fixed boundary total energy of system increase during the application of load and become constant, but with viscous boundary and local damping, the total energy of the system reduces and becomes zero. Viscous boundary absorbs the total energy without reflection, while some reflection occurs in the case of local damping.

Under the Influence of Full Sinusoidal Stress Wave

Figs 12 and 13 show similar result as was with half sine wave. It can be noticed from Figure 14 that in case of half wave displacement at the bottom increases and become constant after some time, but with the application of full wave, displacement at bottom first increases during first half-cycle and then, decreases during second half-cycle, and finally, becomes zero.

Use of Extended Region as Boundary

When a constant damping factor of value 0.3 is provided through the whole extended region and damping forced is applied, as given in the Eq. (3), Figure 15 shows that the extended region is effective in the prevention of reflection of stress wave, but some reflection occurs at the junction

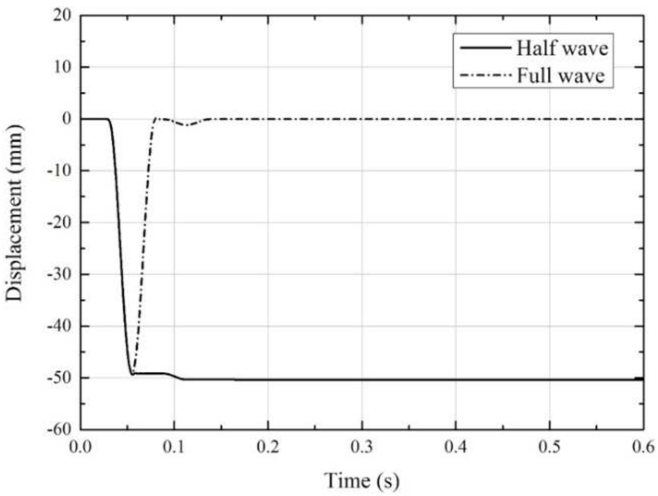

Figure 14: Displacement at the bottom of bar with viscous boundary

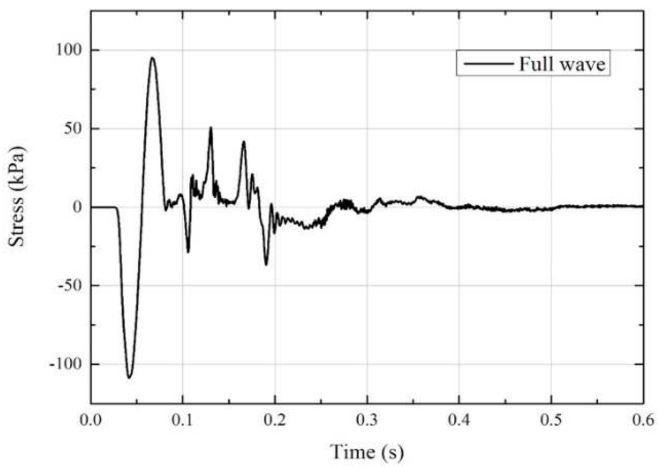

Figure 15: Stress at the junction of extended region with constant damping factor

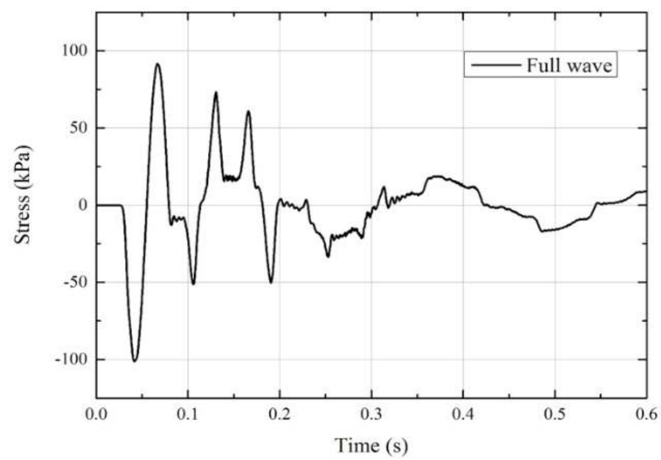

Figure 16: Stress at the junction with maximum value of damping coefficient 0.5

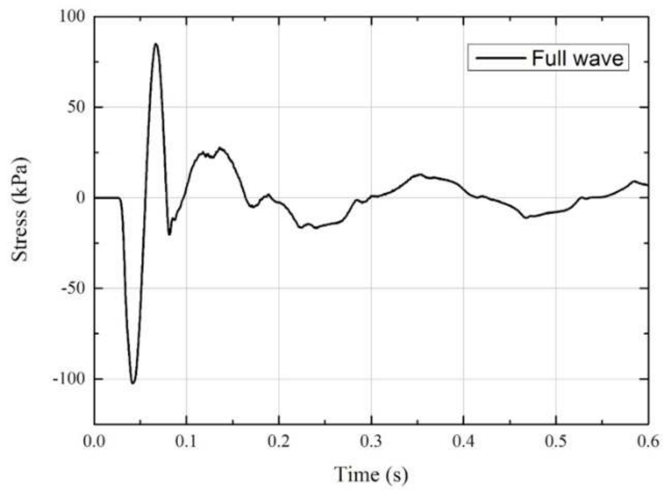

Figure 17: Stress at the junction with maximum value of damping coefficient 0.9

because of change in the properties of the material from bar to extended region.

When a linearly varying damping factor is provided in the extended region, this factor is zero at the junction of extended region and bar, and maximum at the end of the extended region. These two cases are taken into account. In the first case, the maximum value of the damping coefficient is taken 0.5, and in the second case, the maximum value of the damping coefficient is taken 0.9. Figure 16 shows that assumed value of damping factor (0.5) is not sufficient in preventing the reflection, so now the maximum value of damping factor increased up to 0.9 and stress at the junction of extended region and bar is determined. Figure 17 shows an increase in the maximum value of the damping coefficient reduced reflections, but some reflection is still present. Thus, effective absorption of reflected waves may occur with the selection of the correct value of the damping factor.

Conclusion

From the graphs represented above, it can be concluded that when only gravitational acceleration is considered, stress varies, like a wave with same maximum and minimum amplitude, but when local damping is considered stress waves magnitude decreases with time and damped gradually. Then, reaches to a constant value and this decrease in magnitude increases as local damping coefficient increases. Displacement magnitude at the top of the bar is also decreased with time and gradually attain a constant value, when local damping is provided.

It was also found that when a stress wave strikes the fixed boundary, it gets reversed with a double magnitude, but when the standard viscous boundary is considered stress wave does not reverse and damped out gradually.

In case when half-wave is applied, i.e., when only compressive stress is applied, displacement of the bottom point of the bar gets increased with time and never returns to its original position. But, when the full sine wave is applied, i.e., a dynamic force is applied, then the bottom point of the bar moved to a certain distance in the first halfcycle, and then, back to its original position in the next half-cycle. Thus, it can be noticed that standard viscous boundaries are not effective for static analysis.

The application of an extended boundary reduced the amplitude of the stress wave. This prevention of reflection depends on the provided value of the damping factor. It was noticed that despite the high damping factor, some reflections are present; thus, it can be concluded that the performance of the extended boundary is not satisfactory.

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