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Unraveling the Soil-Structure Interaction: A Comparative Analysis of Box Culvert Structural Behavior Under Rigid and Spring Support Conditions

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Abstract

Box culverts are critical infrastructural elements routinely subjected to complex soil–structure interaction phenomena. The conventional approach of assuming rigid foundation supports often leads to an unrealistic distribution of internal forces, potentially resulting in overly conservative or unconservative designs. This study investigates the structural behavior of a reinforced concrete box culvert by comparing a fully rigid support model with subgrade reaction models using spring supports. A finite element analysis was performed under four boundary conditions, namely rigid support, spring support without rigid links, spring support with four rigid links, and spring support with eight rigid links. The analysis evaluated the maximum bending moment (Mmax), axial force (Pmax), shear force (Vmax), and deflection (Δ) of the top slab, vertical walls, and bottom slab. The results indicate that spring-supported models significantly modify the internal force distribution compared with the rigid model, particularly in the bottom slab, where axial forces increased while bending moments and shear forces varied depending on the rigid-link configuration. The inclusion of rigid links produced a more balanced structural response by reducing excessive force concentrations while maintaining the effects of soil–structure interaction. These findings provide practical guidance for selecting appropriate foundation modeling strategies in the numerical analysis and design of reinforced concrete box culverts.

Keywords: Box Culvert; Soil–Structure Interaction; Subgrade Reaction; Spring Support; Finite Element Analysis (FEA)

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1. Introduction

The design and analysis of buried structures, particularly reinforced concrete box culverts, require a nuanced understanding of how these structures interact with the surrounding soil medium. Historically, structural engineers have relied on simplified assumptions regarding the support conditions of these frameworks, frequently defaulting to rigid or fixed supports at the base of the culvert (Audebert & Thibeau, 2021; Bennett et al., 2005). While this approach simplifies the mathematical formulation of the problem, it inherently neglects the reality of soil-structure interaction (SSI), leading to a discrepancy between the analytical predictions and the actual in-situ structural behavior (Elgamal, 2020; Fang, 1991; Terzaghi, 1955). The soil beneath a box culvert does not behave as an unyielding rigid body; rather, it deforms under applied loads, distributing pressures based on its modulus of subgrade reaction(Bowles, 1996; Das, 2019; Winkler, 1867).

The Winkler foundation model, which conceptualizes soil as a series of independent elastic springs, has long been employed to simulate this subgrade reaction (Horvath, 1983; Selvadurai, 1979). However, the implementation of spring supports introduces new complexities, particularly at the interface between the structural elements and the springs (Greco, 2010; Teodoroski & Tschuchnigg, 2023) When finite element models assign springs directly to the nodes of a culvert slab, the lack of rotational restraint can cause localized pin-like behaviors that artificially inflate bending moments and shear forces (Cook et al., 2001; Zienkiewicz & Taylor, 2005). To mitigate this, engineers utilize "rigid links"—elements that constrain the rotational and translational degrees of freedom between the slab and the spring nodes, simulating the continuous nature of a concrete footing resting on soil (Efendi & Eng, 2024; Galvão et al., 2018; Wilson & Habibullah, 1987).

Despite the widespread use of these modeling techniques, there remains a significant gap in the literature regarding a systematic, component-by-component comparison of how different spring and rigid link configurations influence the internal force profiles of box culverts (Abuhajar et al., 2015; Kang et al., 2008). Understanding these variations is paramount, as an overestimation of bending moments leads to uneconomical designs with excessive reinforcement, while an underestimation of shear forces or deflections can compromise structural integrity and serviceability (AASHTO, 2014; ACI Committee 318, 2019b; McGrath et al., 2004). Furthermore, the dynamic interplay between axial compression, shear, and flexure in buried structures demands a holistic evaluation rather than an isolated assessment of singular forces (Burd & Yu, 2021; McAfee & Valsangkar, 2004; Moore, 2001).

This study aims to address this research gap by conducting a comprehensive comparative analysis of a reinforced concrete box culvert under four support conditions: rigid support, spring support without rigid links, spring support with four rigid links, and spring support with eight rigid links. Unlike previous studies, which primarily focused on comparing rigid and spring supports, this research systematically evaluates the influence of different rigid-link configurations on the distribution of bending moments, axial forces, shear forces, and deflections in each structural component of the box culvert. The findings provide a more comprehensive understanding of the influence of soil–structure interaction modeling on structural behavior and offer practical guidance for selecting appropriate boundary conditions in finite element modeling and structural design.

2. Method

2.1. Structural Modeling and Geometric Configuration

Structural Modeling and Geometry The investigation utilized a standard reinforced concrete box culvert modeled using advanced finite element analysis (FEA) software. The geometry consisted of a top slab (roof), two vertical walls, and a bottom slab (floor), all monolithically connected. The structural elements were modeled using shell elements capable of capturing both in-plane (axial and shear) and out-of-plane (bending and transverse shear) behaviors (Aco Wahyudi Efendi et al., 2024; Bathe, 1996; I. A. W. Efendi & Eng, 2024b; Krishna & Rajasekhar, 2018; Logan, 2011). The material properties assigned to the concrete corresponded to standard structural concrete, with a defined modulus of elasticity and Poisson's ratio in accordance with established design codes (European Committee for Standardization, 2004; Fédération internationale du béton, 2013).

2.2. Loading Conditions and Structural Actions

Loading Conditions The culvert was subjected to a comprehensive suite of loads simulating realistic burial conditions. These included the self-weight of the concrete members, vertical earth pressure on the top slab, lateral earth pressure on the vertical walls, and hydrostatic pressure inside the culvert (if applicable) (Coduto, 2001; Lambe & Whitman, 1969). Traffic live loads were applied as distributed pressures on the top slab, conforming to standard highway bridge design specifications (American Association of State Highway & Officials, 2020). The combination of these loads ensures that the culvert experiences the critical stress states typical of shallow and deep burial scenarios (Fredlund & Rahardjo, 1993; Holtz et al., 2011).

2.3. Boundary Conditions and Foundation Support Modeling

Boundary Conditions and Support Configurations The core of this research hinges on the variation of boundary conditions at the base of the culvert. Four distinct models were analyzed:

Model 1: Rigid Support (Without Spring Placement). The nodes at the base of the bottom slab were fully restrained in the vertical and horizontal translations, as well as rotations. This represents the traditional, infinitely stiff foundation assumption(Coduto, 2001).

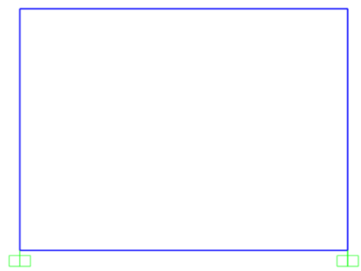

Figure 1. Rigid Support (Without Spring Placement)

Model 2: Spring Support (Without Rigid Link). Vertical and lateral springs, characterized by the modulus of subgrade reaction, were attached directly to the nodes of the bottom slab. No rigid links were employed, allowing for localized rotations and displacements at the spring nodes(Winkler, 1867).

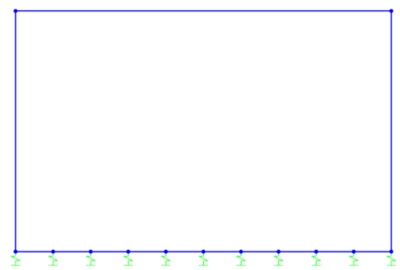

Figure 2. Spring Support (Without Rigid Link)

Model 3: Spring Support (With 4 Rigid Links). Springs were applied similarly to Model 2, but 4 rigid links were introduced along the bottom slab to simulate the continuity and rotational stiffness of the slab-soil interface, restricting differential rotation between adjacent spring nodes (Galvão et al., 2018). The use of four and eight rigid links was intended to investigate the influence of increasing interface continuity between the slab and spring supports. These configurations represent different levels of restraint, allowing the effect of rigid-link density on the structural response to be evaluated.

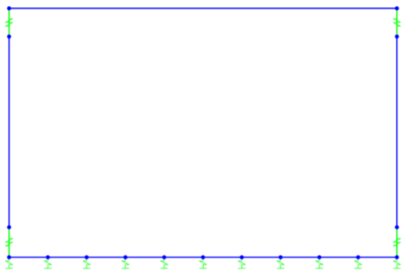

Figure 3. Spring Support (With 4 Rigid Links)

2.4. Data Extraction and Comparative Analysis

Data Extraction and Analysis The analysis output was categorized by structural component: Top Slab, Vertical Wall, and Bottom Slab. For each component, the maximum bending moment (Mmax in kN.m), maximum axial/compression force (Pmax in kN), maximum shear force (Vmax in kN), and maximum deflection (Δ in mm) were extracted. The comparative analysis was conducted by calculating the percentage variations between the rigid model (baseline) and the three spring-configured models, enabling a clear delineation of the soil-structure interaction effects.

3. Result and Discussion

The raw data extracted from the finite element analysis provides a revealing look into the internal force distribution of the box culvert under varying boundary conditions. Table 1 summarizes the structural behavior across all components and parameters.

Table 1. Comparative Analysis of Box Culvert Structural Behavior

Component	Parameter	Unit	Rigid	Spring (0 Rigid Links)	Spring (4 Rigid Links)	Spring (8 Rigid Links)
Top Slab	Mmax	kN.m	200.49	217.44	213.18	191.81
	Pmax	kN	73.92	105.83	62.51	71.90
	Vmax	kN	215.32	271.76	271.76	232.24
	Deflection	mm	1.49	1.45	1.75	1.24
Vertical Wall	Mmax	kN.m	163.50	181.33	162.40	172.89
	Pmax	kN	277.28	321.54	309.89	270.36
	Vmax	kN	73.92	135.94	62.51	71.90
	Deflection	mm	0.26	0.57	0.42	0.24
Bottom Slab	Mmax	kN.m	126.64	195.16	188.92	147.94
	Pmax	kN	0.00	135.94	44.59	33.98
	Vmax	kN	138.15	253.80	244.60	163.48
	Deflection	mm	0.30	0.08	0.02	0.05

Note: Data directly derived from the finite element investigation of the box culvert models.

3.1. Structural Response of the Top Slab

Top Slab Behavior The top slab of a box culvert is primarily subjected to vertical earth pressures and live loads, transferring these forces to the vertical walls through flexure and shear. When analyzing the bending moment (Mmax), the rigid model yielded 200.49 kN.m. The introduction of springs without rigid links caused an 8.4% increase to 217.44 kN.m. This phenomenon occurs because the rigid support forces the bottom corners to act as near-perfect fixed ends, maximizing the negative moment at the wall-slab junction and reducing the positive mid-span moment. In contrast, the spring support allows the walls to rotate and translate slightly, unfixing the corners and pushing the structural behavior closer to a simply supported condition, thereby increasing the positive mid-span moment (Audebert & Thibeau, 2021; Bathe, 1996; Bennett et al., 2005; Bowles, 1996; Cook et al., 2001; Das, 2019; A. W. Efendi, 2024b, 2024a; Elgamal, 2020; Fang, 1991; Galvão et al., 2018; Greco, 2010; Horvath, 1983; Kang et al., 2008; Logan, 2011; McGrath et al., 2004; Moore, 2001; Selvadurai, 1979; Terzaghi, 1955; Wilson & Habibullah, 1987; Winkler, 1867; Zienkiewicz & Taylor, 2005).

Interestingly, as rigid links are introduced (4 and 8 links), the Mmax begins to decrease (213.18 kN.m and 191.81 kN.m, respectively). The rigid links restore some of the lost rotational stiffness at the interface, better simulating the monolithic nature of the structure resting on a continuous soil medium(Burd & Yu, 2021; McAfee & Valsangkar, 2004). The axial force (Pmax) in the top slab peaked drastically at 105.83 kN in the spring model without rigid links, a 43% increase from the rigid model (73.92 kN). This is attributed to the localized stress concentrations at the unsupported spring nodes, which induce arching effects within the slab. The inclusion of 4 rigid links dramatically reduced Pmax to 62.51 kN, showcasing how rigid links distribute localized compressive stresses along the slab (Abuhajar et al., 2015; ACI Committee 318, 2019a; American Association of State Highway & Officials, 2020; Bowles, 1996; Coduto, 2001; Das, 2019; Fang, 1991; Fédération internationale du béton, 2013; Fredlund & Rahardjo, 1993; Galvão et al., 2018; Holtz et al., 2011;

Lambe & Whitman, 1969; Selvadurai, 1979; Teodoroski & Tschuchnigg, 2023; Terzaghi, 1955; Winkler, 1867; Zienkiewicz & Taylor, 2005).

The shear force (Vmax) exhibited a similar trend, surging from 215.32 kN in the rigid model to 271.76 kN in both the 0-link and 4-link spring models. This 26% increase represents a critical design concern; shear reinforcement (stirrups) requirements would escalate significantly if the spring condition is ignored (Moore, 2001; McGrath et al., 2004). The 8-rigid-link model mitigated this to 232.24 kN, closely aligning with the rigid baseline. Deflection (Δ) remained relatively constrained across all models, though the 4-rigid-link model showed a maximum of 1.75 mm, likely due to the specific interaction of the slab's flexural stiffness with the partially restrained spring nodes.

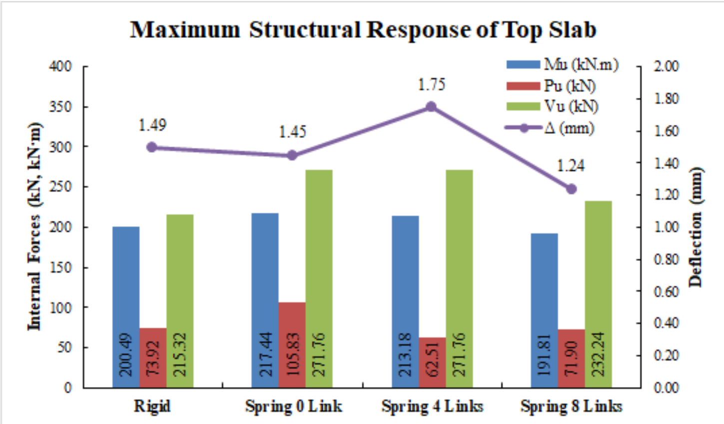

Figure 4. Maximum Structural Response of Top Slab

3.2. Structural Response of the Vertical Walls

Vertical Wall Behavior The vertical walls act as the primary load-transfer elements, experiencing complex combinations of axial compression from the top slab and bending moments from lateral earth pressure. Under rigid support assumptions, the wall bending moment (Mmax) was 163.50 kN.m. Transitioning to a spring support without rigid links increased the moment to 181.33 kN.m. This increase is directly tied to the loss of rotational fixity at the wall-base junction; as the base becomes flexible, the wall behaves more like a propped cantilever rather than a fixed-end beam, altering the inflection point and magnifying the positive moment (AASHTO, 2020; ACI Committee 318, 2019; EN 1992-1-1, 2004; fib, 2013; Coduto, 2001; Lambe & Whitman, 1969; Fredlund & Rahardjo, 1993; Holtz et al., 2011; Burd & Yu, 2021; McAfee & Valsangkar, 2004; Moore, 2001; McGrath et al., 2004; Kang et al., 2008; Abuhajar et al., 2015; Galvão et al., 2018; Teodoroski & Tschuchnigg, 2023; Bowles, 1996; Das, 2019; Fang, 1991; Terzaghi, 1955; Winkler, 1867).

The axial force (Pmax) in the walls is strictly compressive, resulting from the vertical loads channeled from the top slab. The rigid model produced a Pmax of 277.28 kN. The spring models consistently showed higher axial forces, peaking at 321.54 kN without rigid links. Because the springs allow the bottom slab to deflect and relieve some of the bending stress, the structure compensates by mobilizing more axial stiffness—essentially pushing the loads down through the stiffest vertical paths, which are the walls.

A highly anomalous yet mechanically explainable finding is the shear force (Vmax) in the walls. The rigid model yielded a Vmax of 73.92 kN, which spiked to 135.94 kN in the spring model without rigid links. Strikingly, this value exactly matches the peak axial force in the top slab for the same model. The identical numerical values observed for the wall shear force and the top slab axial force may indicate a close interaction in the force transfer mechanism at the wall–slab junction. However, further analysis of the internal force distribution would be required to explicitly verify the equilibrium mechanism at this interface. The 4-rigid-link model saw Vmax plummet to 62.51 kN, indicating that the rigid links successfully transferred the shear back into the slab and soil interface, preventing the corner from absorbing the full brunt of the unbalanced thrust.

Wall deflection was highest in the 0-rigid-link model (0.57 mm), nearly double that of the rigid model (0.26 mm). However, the 8-rigid-link model reduced deflection to 0.24 mm, demonstrating that a sufficiently dense rigid link configuration can effectively replicate the restraint provided by an infinitely rigid foundation, while still allowing the realistic vertical settlement profile of the soil.

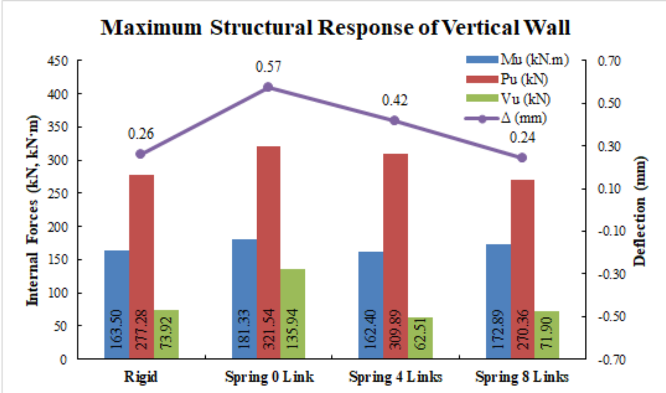

Figure 5. Maximum Structural Response of Vertical Wall

3.3. Structural Response of the Bottom Slab

Bottom Slab Behavior The bottom slab represents the interface where soil-structure interaction is most critical. In the rigid model, the base is assumed entirely unyielding, leading to a bending moment (Mmax) of 126.64 kN.m. When springs are introduced without rigid links, the Mmax skyrockets by 54% to 195.16 kN.m. This massive increase stems from the fact that independent springs allow the soil to deform under the slab, removing the uniform support assumption. Concentrated loads from the walls cause the slab to punch downward into the soil, generating massive hogging and sagging moments between the spring nodes.

Perhaps the most profound discovery lies in the axial force (Pmax) of the bottom slab. The rigid model registered a Pmax of 0.00 kN. Because a fully fixed base cannot slide or displace horizontally, no thrust is generated along the length of the slab; it acts purely in flexure. Conversely, the spring models allow the slab to flex and spread laterally into the soil under vertical loads, inducing significant axial compression. The 0-rigid-link model produced a Pmax of 135.94 kN. As rigid links are added, this axial force decreases (44.59 kN for 4 links; 33.98 kN for 8 links) because the rigid links bind the slab's horizontal translation, simulating the friction and passive resistance of the soil mass (Burd & Yu, 2021; McAfee & Valsangkar, 2004; Moore, 2001; McGrath et al., 2004; Kang et al., 2008; Abuhajar et al., 2015; Galvão et al., 2018; Teodoroski & Tschuchnigg, 2023; AASHTO, 2020; ACI Committee 318, 2019; EN 1992-1-1, 2004; fib, 2013; Coduto, 2001; Lambe & Whitman, 1969; Fredlund & Rahardjo, 1993; Holtz et al., 2011; Bowles, 1996; Das, 2019; Winkler, 1867).

Shear force (Vmax) in the bottom slab follows a parallel trajectory to the bending moment. The rigid model's Vmax was 138.15 kN, but the 0-rigid-link model saw a terrifying 83.7% increase to 253.80 kN. Such a shear force would necessitate heavy shear reinforcement, significantly altering the design economy. The 8-rigid-link model brought the Vmax down to a much more manageable 163.48 kN. Deflections in the bottom slab were actually highest in the rigid model (0.30 mm). This is because the rigid restraints prevent the entire slab from settling uniformly; instead, the mid-span is forced to bear the full brunt of the internal forces without the soil yielding to redistribute the load. The spring models showed minimal deflection (as low as 0.02 mm with 4 rigid links) because the soil yields locally, allowing the slab to find a more natural, less stressed equilibrium point(Audebert & Thibeau, 2021; Bennett et al., 2005; Elgamal, 2020; Galvão et al., 2018; Greco, 2010; Kang et al., 2008; Logan, 2011) .

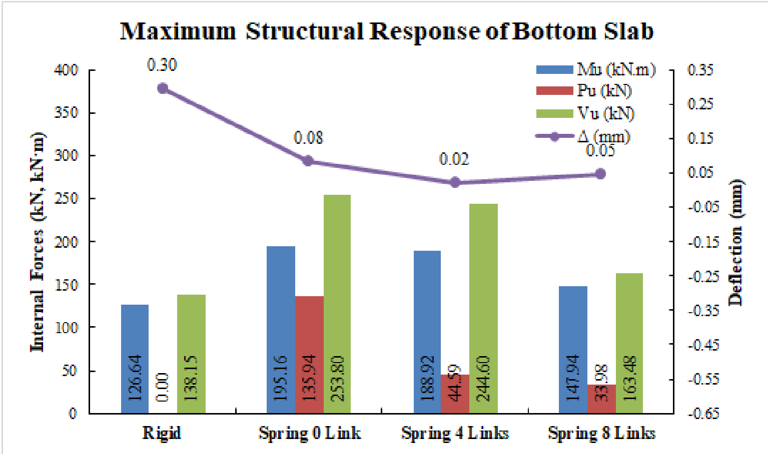

Figure 6. Maximum Structural Response of Bottom Slab

3.4 Implications for Structural Design and Numerical Analysis

Implications for Design and Analysis The comparative data unambiguously demonstrates that modeling a box culvert with rigid supports is fundamentally inadequate for capturing the true structural response. The rigid assumption creates a false sense of security regarding bending moments and shear forces in the bottom slab while completely neglecting the critical axial forces generated by soil-structure interaction .

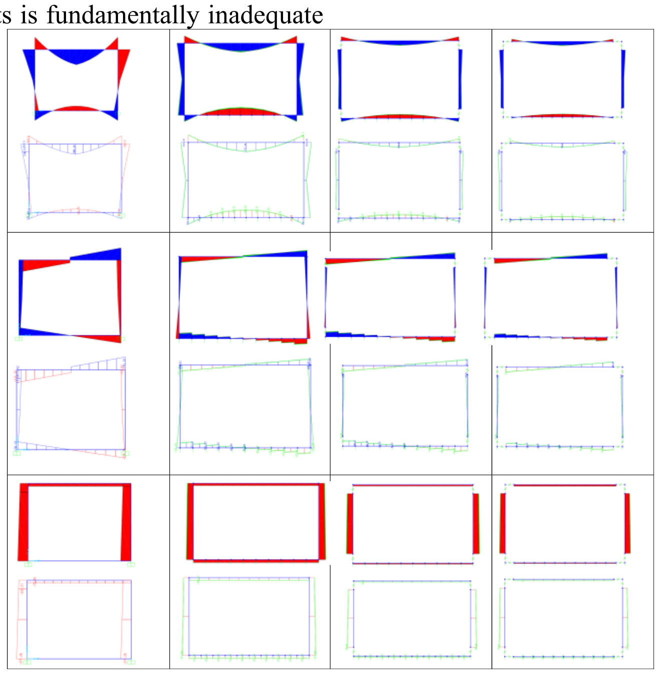

Figure 7. Internal Force Behavior That Occurs in The Treatment Without Spring Placement (Rigid) Vs. with Spring Placement (Subgrade Reaction)

On the other hand, modeling springs without rigid links overcompensates, resulting in extreme localized forces—particularly the 83.7% increase in bottom slab shear and the 54% increase in bottom slab moment. This leads to needlessly expensive designs. The inclusion of rigid links acts as a necessary mechanical mediator. The 8-rigid-link model consistently produced results that balanced the extremes: it retained the realistic settlement and axial force generation of the spring models, but restrained the exaggerated localized rotations and stress concentrations. This confirms that a Winkler foundation model, when combined with an appropriately dense rigid link mesh, provides the most accurate and economically viable simulation of a box culvert resting on a subgrade.

The observed trends are generally consistent with previous studies on soil–structure interaction in buried concrete structures. Earlier research has shown that modeling the foundation as a rigid support tends to underestimate the influence of soil deformability, resulting in differences in the distribution of bending moments, shear forces, and axial forces compared with spring-based foundation models (Abuhajar et al., 2015; Kang et al., 2008; McGrath et al., 2004). Similarly, the present study demonstrates that incorporating subgrade reaction through spring supports significantly alters the internal force distribution, particularly in the bottom slab, highlighting the importance of realistic boundary condition modeling in finite element analysis.

In addition, the reduction of localized force concentrations achieved by introducing rigid links agrees with the findings of Galvão et al. (2018), who reported that improving the continuity of the slab–foundation interface enhances numerical stability and produces structural responses that better represent actual soil restraint. Although the magnitude of the internal forces differs due to variations in geometry, loading conditions, and soil parameters, the overall trend observed in this study is consistent with previous research, confirming the significance of soil–structure interaction in the structural analysis of box culverts.

4. Conclusion

This study systematically evaluated the structural behavior of a box culvert under four distinct boundary condition models: rigid, spring without rigid links, spring with 4 rigid links, and spring with 8 rigid links. By analyzing the maximum bending moment (Mmax), axial force (Pmax), maximum shear force (Vmax), and deflection (Δ) across the top slab, vertical walls, and bottom slab, the following critical conclusions were drawn:

The Inadequacy of the Rigid Model: The traditional rigid support model completely suppresses the generation of axial forces in the bottom slab (Pmax = 0.00 kN) and artificially minimizes bending moments and shear forces in the bottom slab. This model fails to recognize that soil yields, and this yielding induces horizontal thrusts and redistributed flexural stresses that a rigid base cannot absorb. Designing based solely on rigid assumptions may result in under-reinforced bottom slabs vulnerable to shear and axial failure.

The Peril of Unmodified Spring Models: Utilizing springs without rigid links creates artificially compliant nodes that act as stress concentrators. This model produced the highest forces in almost every category, including a 54% increase in bottom slab Mmax and an 83.7% increase in bottom slab Vmax compared to the rigid model. While it captures the axial thrust (Pmax = 135.94 kN), it does so at the expense of grossly overestimating flexural and shear demands, leading to highly uneconomical designs.

The Efficacy of Rigid Links: The introduction of rigid links significantly tempers the extreme forces generated by pure spring models. The 8-rigid-link model emerged as the most balanced approach, reducing the bottom slab Mmax from 195.16 kN.m (0 links) to 147.94 kN.m, and Vmax from 253.80 kN to 163.48 kN, while still preserving a realistic axial thrust of 33.98 kN. The rigid links effectively simulate the continuous nature of the concrete slab resting on the soil, preventing the independent, localized deformation of individual springs.

Global Structural Behavior: The structural behavior of the culvert is highly interdependent. Changes in the base restraint directly influence the shear and moment transfer at the wall-slab junctions. The symmetry observed between the top slab axial force and the wall shear force in the pure spring model (both exactly 135.94 kN) highlights the intense force redistribution that occurs when boundary conditions are altered.

In summation, the analysis unequivocally advocates for the abandonment of purely rigid base assumptions in box culvert design. Engineers must incorporate subgrade reaction via spring supports to capture realistic axial forces and deflections. However, to avoid hyper-conservative and costly outcomes, it is imperative to couple these springs with an adequate number of rigid links. The 8-rigid-link configuration provides a robust, mechanically sound approximation of soil-structure interaction, ensuring structural safety without compromising economic viability.

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