

Innovative Cost-optimized Framed Abutments: a Finite Element Comparative Study with Conventional Systems

Kare Rahul Gorakhnath

¹PG Scholar, Department of Civil Engineering
World College of Technology and Management
Gurgaon, India

Ankit Sethi

Assistant Professor, Department of Civil Engineering
World College of Technology and Management
Gurgaon, India

Abstract - The present study proposes an economical and structurally efficient alternative to conventional wall-type abutments used in highway underpass structures. Recent revisions in guidelines issued by the National Highways Authority of India have restricted the use of circular column abutments with gap slab arrangements, creating the need for a practical replacement system. A framed-type abutment system was developed and analysed using a three-dimensional finite element model in MIDAS Civil for a 30 m span underpass. The proposed system consists of inclined frame members, intermediate slabs, and a raft foundation to improve load transfer and reduce lateral earth pressure effects. Soil-structure interaction and seismic loading were considered as per IRC provisions. The analysis showed satisfactory structural performance with lower bending moments, reduced material requirement, and shallow foundation depth compared to conventional abutments. The proposed framed abutment demonstrated superior structural efficiency, reduced foundation demand, and substantial cost savings compared to conventional systems, indicating strong potential for future highway underpass applications.

Keywords - Framed Abutment, Underpass Structure, Finite Element Analysis, Cost Optimization, Soil-Structure Interaction.

I. INTRODUCTION

1.1 General Background

Bridge abutments are important structural components that support the bridge superstructure and retain the earth fill behind the bridge. They transfer vertical loads from the superstructure and resist lateral loads caused by earth pressure, live load surcharge, braking force, and seismic effects. Therefore, the behaviour of abutments directly affects the stability, durability, and economy of bridge structures. In India, conventional wall-type abutments are commonly used because of their simple design procedure and ease of construction. However, with increasing embankment heights, wider carriageways, and higher traffic loading, these systems often become uneconomical due to excessive concrete and reinforcement requirements.

Recently, the National Highways Authority of India restricted the use of circular column-type abutments with gap slab arrangements for underpass structures having closed reinforced earth walls. Due to this revision, designers are mainly dependent on conventional wall-type abutments, which significantly increases the project cost. This situation has created the need for an economical and structurally efficient

alternative abutment system suitable for modern highway infrastructure projects.

1.2 Limitations of Conventional Abutments

The main limitation of conventional wall-type abutments is the large lateral earth pressure acting on the retaining wall. As the retained soil height increases, the magnitude of earth pressure also increases, resulting in larger bending moments and shear forces. To resist these forces, thicker wall sections and longer heel slabs are required. However, larger heel slabs attract additional backfill weight, which further increases the structural demand on the foundation system. Consequently, higher quantities of concrete and reinforcement are required, making the structure expensive and difficult to construct.

In urban highway projects, conventional abutments also create construction difficulties due to limited working space and deep excavation requirements. In weak soil conditions, the foundation size increases further because of bearing pressure limitations. Therefore, conventional wall-type abutments are not always suitable for modern highway underpass structures where economy and constructability are important considerations.

1.3 Need for Framed-Type Abutment

To overcome the limitations of conventional systems, the present study proposes an advanced framed-type abutment system. The proposed arrangement consists of inclined frame members, intermediate slabs, and a raft foundation. The intermediate slabs divide the vertical shaft into smaller segments and reduce bending moments in structural members. The inclined back shaft helps reduce the horizontal effect of earth pressure and surcharge loading. In addition, a toe wall with earth filling is provided to utilise passive earth pressure and improve resistance against sliding and overturning. The raft foundation distributes the load uniformly and reduces bearing pressure on the soil.

Due to these structural features, the framed-type abutment system reduces concrete and reinforcement consumption while maintaining structural safety and stability. Hence, the system can provide an economical and practical alternative for underpass structures and highway bridge projects.

1.4 Role of Finite Element Analysis

In the present study, MIDAS Civil was used for three-dimensional finite element analysis of the proposed framed-type abutment system. The analysis included dead load, live load, earth pressure, surcharge load, braking force, and seismic loading as per relevant IRC provisions. Soil-structure

interaction was also considered using elastic spring supports below the raft foundation.

The finite element model helped evaluate bending moments, stress distribution, structural deflection, base pressure, and overall stability of the system. This detailed analysis provided a realistic understanding of the structural behaviour and efficiency of the proposed abutment arrangement.

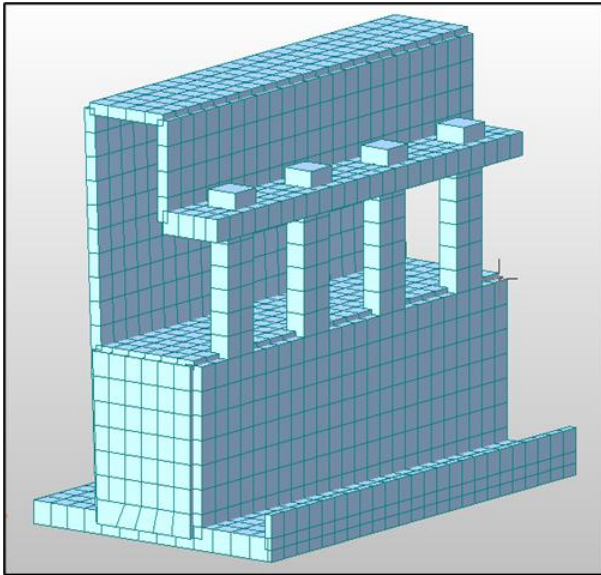


Fig. 1. Finite element model of the framed abutment

1.5 Problem Statement

Due to revised National Highways Authority of India guidelines, the use of conventional wall-type abutments has increased in highway underpass projects. However, these systems often become costly because of large earth pressure forces and heavy structural sections. Existing studies on framed-type abutments for highway applications are limited, particularly those involving finite element analysis and cost optimisation. Therefore, there is a need to develop a safe, economical, and structurally efficient alternative abutment system suitable for future highway projects.

1.6 Aim and Objectives of the Study

The main aim of this study is to develop and analyse a framed-type abutment system and compare its structural performance and cost with conventional wall-type abutments. The study also aims to reduce construction cost and material consumption while maintaining structural safety against sliding, overturning, and bearing failure. In addition, the research evaluates soil–structure interaction, seismic behaviour, and overall structural performance using finite element modelling techniques.

1.7 Significance of the Study

The present research provides a modern and economical alternative to conventional abutment systems used in highway underpass structures. The proposed system offers improved structural behaviour, reduced material consumption, and easier construction methodology. The study also establishes a practical finite element analysis approach for future bridge

substructure projects. Therefore, the outcomes of this research will be useful for bridge engineers, researchers, consultants, and highway authorities involved in highway infrastructure development.

II. LITERATURE REVIEW

Rankine (1857) [1] developed a classical earth pressure theory for dry and cohesionless soils by assuming a smooth vertical wall and level backfill. The theory provided simple equations for active and passive earth pressure and is still widely used for preliminary design. However, the method does not consider wall friction and soil nonlinearity.

Coulomb (1776) [2] proposed a wedge theory based on force equilibrium. His method considered wall friction, wall inclination, and sloping backfill conditions. The theory became more suitable for practical retaining structures and later formed the basis for seismic earth pressure analysis.

Terzaghi (1943) [3] established the basic principles of modern soil mechanics and introduced the concept of effective stress. His work explained soil behaviour under loading and provided the foundation for bearing capacity, settlement, and stability analysis used in bridge foundation design. Bowles (1996) [4] further presented practical methods for foundation and retaining structure design, including earth pressure, bearing capacity, and settlement analysis.

Chang and Cooke (1983) [5] studied soil–structure interaction in bridge abutments and observed that conventional earth pressure theories may underestimate actual pressure because interaction between deck, embankment, and abutment is generally ignored. Their study highlighted the importance of numerical analysis in bridge substructure design.

Merifield et al. (2007) [6] used finite element limit analysis to study retaining wall stability and reported that numerical methods can capture realistic failure mechanisms and improve design optimisation. Christian and Chan (1990) [7] analysed reinforced retaining walls using finite element methods and observed that reinforcement improves stability and reduces wall movement.

Wood (1973) [8] studied earthquake-induced earth pressure and showed that dynamic earth pressure may become significantly higher than static pressure. Mononobe and Matsuo (1929) [9] and Okabe (1924) [10] extended Coulomb's theory for seismic conditions by introducing pseudo-static earthquake forces. The Mononobe–Okabe method is still widely used in seismic retaining wall design.

Reid and Sullivan (2005) [11] studied bridge abutments using nonlinear finite element analysis and found that soil nonlinearity and realistic boundary conditions significantly influence earth pressure and displacement behaviour. Kazmierczak and Banks (1986) [12] investigated frame-type abutments and reported that frame systems provide better stiffness and load distribution compared to conventional cantilever systems.

Nakashima and Watanabe (1995) [13] studied the seismic response of bridge abutments and observed that soil–structure interaction and abutment flexibility strongly affect seismic performance. Duncan and Wright (2005) [14] further explained the importance of shear strength, pore pressure, and slope stability in retaining structure design.

Santosh Kumbar et al. (2022) studied different types of bridge abutments under seismic loading and observed that box-type abutments performed better in terms of bending moment, shear force, and structural stability. The study also confirmed the importance of finite element analysis and seismic evaluation in bridge design.

Swamini Adhikari and M. N. Bajad (2025) compared gravity, cantilever, and counterfort abutments and concluded that counterfort abutments are more suitable for large heights, while cantilever abutments provide balanced economy and performance for medium heights.

Tayyaba Choudhari and R. Shreedhar (2020) studied piled abutments and observed improved stability and lower bending moments in weak soil conditions. The study also reported better resistance against overturning and lateral soil pressure compared to conventional wall-type abutments.

Bhandari and Pandey (2015) [19] studied optimisation of retaining structures using finite element techniques and reported that numerical modelling helps reduce material consumption while maintaining safety. Raju (2012) [20] compared counterfort and cantilever retaining walls and concluded that counterfort systems become more economical for larger retaining heights.

From the reviewed literature, it is clear that the performance of bridge abutments depends on earth pressure, soil condition, geometry, seismic loading, and foundation behaviour. Most researchers recommended finite element analysis and soil-structure interaction modelling for safe and economical bridge substructure design. However, limited research is available on framed-type abutments for highway underpass structures. Therefore, the present study focuses on developing and analysing an economical framed-type abutment system using finite element analysis.

III. METHODS OF ANALYSIS

3.1 General

The present study was carried out to develop and evaluate an advanced framed-type abutment system for highway underpass structures. The methodology included modelling, analysis, stability evaluation, and cost comparison of different abutment systems. The study mainly focused on improving structural efficiency and reducing construction cost while maintaining safety and serviceability requirements as per IRC provisions.

Three different abutment systems were considered in the study for comparison:

1. Conventional Wall-Type Abutment
2. Single Circular Column Abutment with Gap Slab and Closing RE Wall
3. Counterfort Abutment.
4. Proposed Framed-Type Abutment

The conventional systems were analysed using spreadsheet-based calculations, whereas the proposed framed-type abutment was analysed using MIDAS Civil through three-dimensional finite element modelling.

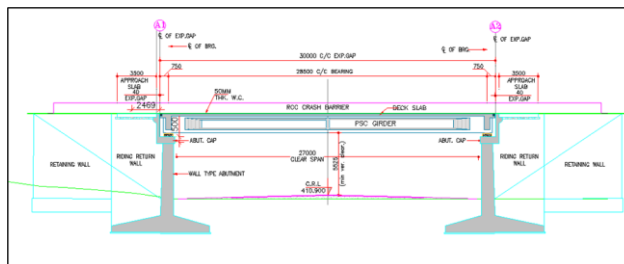


Fig. 2. GA Drawing of wall type Abutment

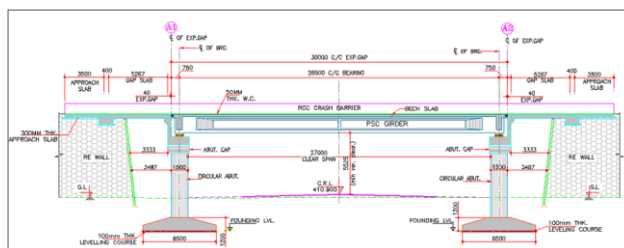


Fig. 3. GA Drawing of Circular column & Gap Slab

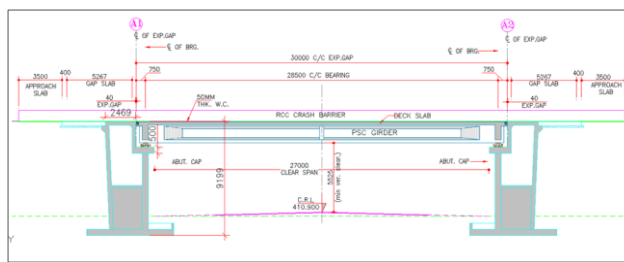


Fig. 4. GA Drawing of Framed Type Abutment

3.2 Bridge and Soil Parameters

The proposed abutment system was developed for a reinforced concrete two-lane bridge underpass structure. The important bridge, soil, and seismic parameters considered in the analysis are given in Table 3.1.

TABLE I. SALIENT FEATURES AND DESIGN PARAMETERS

Parameter	Value
Span Length	28.50 m
Overall Width	12.00 m
Clear Carriageway Width	11.00 m
Wearing Coat Thickness	65 mm
Grade of Concrete	M35 / M40
Grade of Reinforcement	Fe550
Unit Weight of RCC	25 kN/m ³
Soil Friction Angle	30°
Coefficient of Friction	0.50

Live Load Surcharge	2.4 t/m ²
Seismic Zone	Zone IV
Soil Type	Medium Soil
Importance Factor	1.20
Net Safe Bearing Capacity	20 t/m ²

The modulus of subgrade reaction was calculated based on allowable settlement criteria. The calculated value of modulus of subgrade reaction was 1333 kN/m³.

3.3 Modelling in MIDAS Civil

The proposed framed-type abutment was modelled using finite element analysis in MIDAS Civil. The structural system consisted of vertical framed shafts, intermediate diaphragm slabs, inclined rear walls, toe retaining walls, and raft foundations. The inclined rear wall was provided to reduce the horizontal effect of earth pressure, while the toe wall helped mobilise passive resistance for improving stability.

Backfill soil layers were considered with realistic material properties to simulate actual field conditions. Soil–structure interaction was incorporated by providing elastic spring supports below the raft foundation in both vertical and horizontal directions.

The model was discretised using quadrilateral and hexahedral finite elements. Mesh refinement studies were carried out to obtain accurate stress distribution and displacement behaviour. Convergence checks were performed by varying mesh density and observing changes in stress and deflection values.

3.4 Material Properties

The material properties adopted in the analysis were based on IRC and IS code provisions. M35 grade concrete was used depending on stress demand, while Fe550 reinforcement steel was considered for all structural members. Soil properties such as elastic modulus, unit weight, and Poisson’s ratio were adopted from geotechnical investigation data and IRC recommendations.

3.5 Load Calculations and Assignments

All important loads acting on the abutment were considered as per IRC provisions. The loading included dead load, superimposed dead load, earth pressure, live load surcharge, braking force, wind load, and seismic force.

Dynamic earthquake earth pressure was evaluated using Mononobe–Okabe theory considering seismic acceleration effects in the backfill soil.

TABLE II. LOAD CONSIDERED IN THE ANALYSIS

Load Type	Description	Code Reference
Dead Load	Self-weight and superimposed load	IRC:6
Earth Pressure	Active and passive	Rankine /

	earth pressure	Coulomb Theory
Live Load	IRC Class A and 70R Loading	IRC:6
Surcharge Load	Vehicle surcharge load	IRC:6
Braking Load	Vehicle braking effect	IRC:6
Wind Load	Wind effect on structure	IRC:6
Seismic Load	Earthquake loading	IRC:6 & IRC:78
Dynamic Earth Pressure	Seismic earth pressure	Mononobe–Okabe Theory

Multiple load combinations were developed as per IRC:6–2017 and IRC:78 provisions for stability checks, base pressure checks, ultimate limit state, and serviceability limit state analysis.

3.6 Earth Pressure and Seismic Parameters

Earth pressure coefficients were calculated using Rankine and Coulomb earth pressure theories considering soil friction angle, wall friction angle, surcharge intensity, and soil unit weight. Dynamic earth pressure coefficients were evaluated using seismic parameters corresponding to Zone IV conditions.

TABLE III. SEISMIC PARAMETERS

Parameter	Value
Seismic Zone	IV
Zone Factor	0.24
Importance Factor	1.20
Response Reduction Factor	1.0
Soil Type	Medium Soil
Horizontal Seismic Coefficient	0.081
Vertical Seismic Coefficient	0.054

3.7 Structural Performance Evaluation

The structural behaviour of the proposed abutment system was evaluated based on bending moment, shear force, stress distribution, structural displacement, and base pressure response. Stability checks against sliding, overturning, and bearing failure were also carried out.

Stress contour plots and reinforcement requirements were studied to identify critical regions in the structure. Serviceability requirements such as crack control and displacement limits were also verified.

3.8 Cost Analysis and Optimisation

A detailed cost comparison was carried out between the three abutment systems based on concrete quantity, reinforcement consumption, excavation volume, foundation depth, and shuttering requirements. The optimisation process aimed to identify the most economical structural configuration without compromising safety and serviceability.

The proposed framed-type abutment demonstrated significant reduction in concrete and reinforcement quantity compared to conventional wall-type abutments, resulting in considerable project cost savings.

3.9 Validation of Results

The analytical results obtained from finite element analysis were validated using classical soil mechanics equations and standard literature findings. Earth pressure values, load transfer behaviour, and stability checks obtained from the numerical model were compared with manual calculations to ensure accuracy and reliability of the proposed methodology.

IV. RESULTS AND DISCUSSION

4.1 General

The results obtained from the analysis and design of the proposed framed-type abutment were compared with conventional wall-type abutment and single circular column abutment with gap slab arrangement. The comparison was carried out based on stability, base pressure, material consumption, structural behaviour, seismic performance, and construction economy.

4.2 Stability Check

The stability of the framed-type abutment was checked against sliding and overturning under critical loading conditions.

TABLE IV. FOS AGAINST SLIDING & OVERTURNING

Parameter	Minimum Value	Maximum Value
FOS Against Sliding	1.03	1.34
FOS Against Overturning	1.63	4.53

The obtained factors of safety were found to satisfy IRC requirements under all critical loading conditions. The inclined rear shaft and toe wall improved the overall stability by reducing overturning effects and mobilising passive earth resistance.

4.3 Base Pressure Check

The base pressure values obtained from finite element analysis were within the permissible bearing capacity limits under normal and seismic conditions.

TABLE V. BASE PRESSURE

Parameter	Value
Maximum Base Pressure	23.2 t/m ²
Minimum Base Pressure	0.5 t/m ²
Allowable SBC (Normal)	28 t/m ²
Allowable SBC (Seismic)	35 /m ²

4.4 Iterative Study of Base Width

An iterative analysis was carried out by varying the base width of the framed-type abutment to obtain the most economical and structurally stable configuration. The study considered foundation depth, required safe bearing capacity, and stability requirements.

The analysis showed that increasing base width improved sliding and overturning resistance and reduced soil pressure. However, it also increased excavation depth and foundation cost. Among all cases studied, the 8 m base width was found to be the most suitable configuration.

The selected configuration required only 0.5 m excavation depth and achieved satisfactory stability with factor of safety values greater than the permissible limits. The required bearing pressure of 22.3 t/m² also matched well with the available soil capacity. Therefore, the 8 m base width was adopted for final design and analysis.

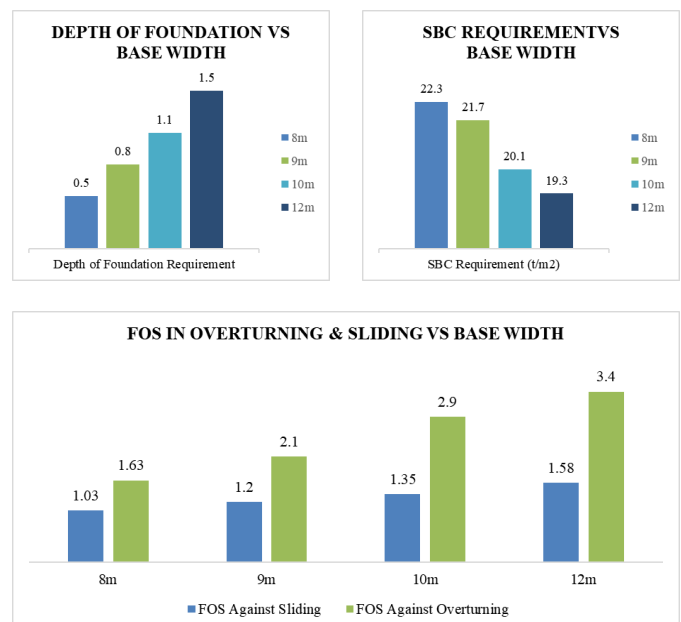


Fig. 5. Iterative Study of base width

4.5 Mesh Convergence Study

A mesh convergence study was carried out by varying shell element sizes from 1.0 m to 0.20 m. The study compared critical responses such as plate bending moment, shear force, and horizontal displacement under earth pressure loading.

The results indicated that the variation between 0.50 m mesh size and finer meshes remained within 2%. Therefore, the 0.50 m mesh size was considered sufficient for obtaining accurate structural behaviour while maintaining computational efficiency. Hence, the same mesh size was adopted for final finite element analysis.

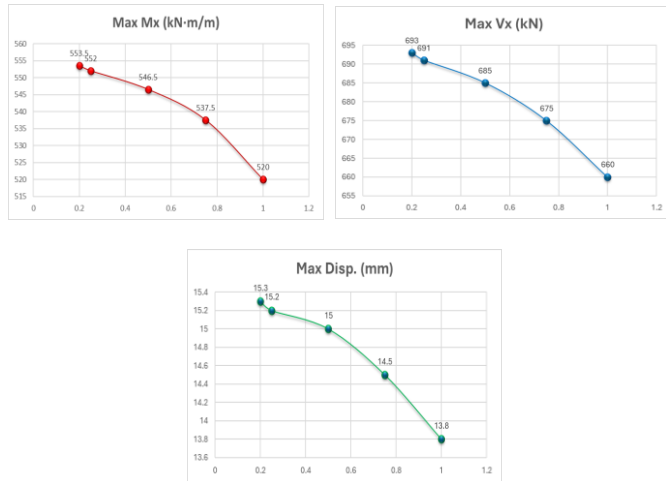


Fig. 6. Plate Mesh Convergence Study

4.6 Cost Comparison of Different Abutment Systems

The comparative cost analysis of different abutment systems is presented in Fig.7. The comparison was carried out based on standard Schedule of Rates (SOR) values. Rate for concrete is 6500 Rs per Cum & A reinforcement steel rate of ₹65 per kg was considered.

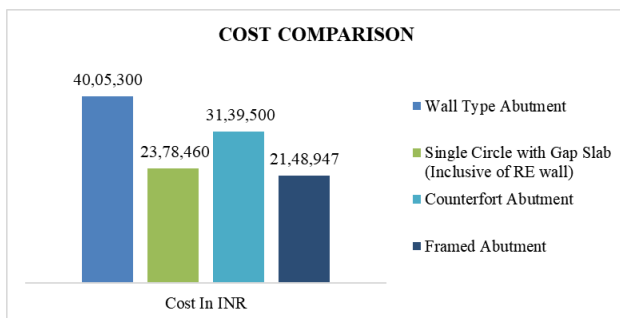


Fig. 7. Cost comparison between various options.

The framed-type abutment was found to be the most economical option among all alternatives studied. The proposed system achieved approximately 46.4% cost saving compared to the conventional wall-type abutment and around 9.6% savings compared to the circular column abutment with gap slab arrangement.

The major reason for cost reduction was the efficient frame action, which reduced bending moments and allowed the use of smaller structural sections with lower material consumption.

TABLE VI. COMPARISON OF FOUNDATION PARAMETERS

Abutment Type	Base Width (m)	Required SBC (t/m ²)	Excavation Depth (m)
Wall-Type Abutment	9.0	27	3.0
Single Circular Column with Gap Slab	8.5	24	3.0
Counterfort Abutment	9.2	26	3
Framed-Type Abutment	8.0	22.3	0.5

The proposed framed-type abutment required the least excavation depth and lowest bearing pressure among all options. The reduction in foundation depth significantly decreased excavation quantity, backfilling, and construction time. The compact foundation geometry also makes the system suitable for congested underpass locations.

TABLE VII. COMPARISON OF MATERIAL QUANTITIES

Abutment Type	Concrete (m ³)	Reinforcement Steel (kg)
Wall-Type Abutment	274	32,220
Single Circular Column with Gap Slab	156	18,683
Counterfort Abutment	233	25,000
Framed-Type Abutment	149	20,561

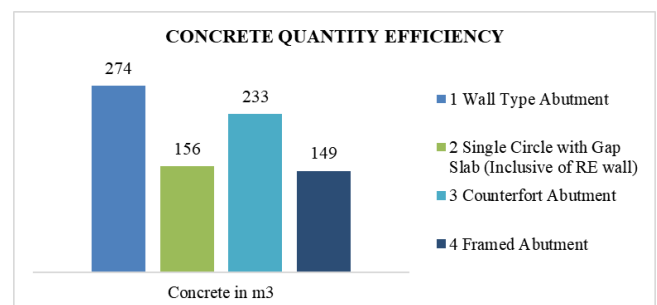


Fig. 8. Concrete quantity efficiency

The framed-type abutment required the minimum quantity of concrete among all options studied. Although the circular column arrangement used slightly lower steel quantity, the framed system provided better overall stability, improved constructability, and compliance with updated highway authority guidelines.

The reduced material consumption directly contributed to lower project cost and improved construction efficiency.

4.9 Structural and Seismic Performance

The structural behaviour of the framed-type abutment was observed to be superior due to efficient load redistribution through frame action. The intermediate slabs reduced bending moments in the inclined rear wall and improved overall stiffness of the structure.

The inclined shaft arrangement also reduced the effect of lateral earth pressure and seismic forces. The finite element analysis indicated lower stress concentration and reduced base pressure under seismic load combinations compared to conventional systems.

The lower structural mass and reduced foundation dimensions helped minimise seismic inertia forces, thereby improving earthquake resistance. The proposed system therefore demonstrated better seismic performance and structural stability under dynamic loading conditions.

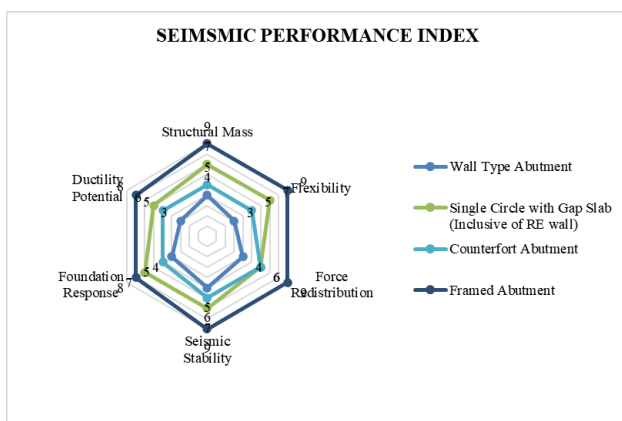


Fig. 9. Seismic performance index

4.10 Constructability and Practical Advantages

From a construction point of view, the framed-type abutment provided better workability due to reduced foundation depth and compact geometry. The lower excavation quantity reduced construction time and simplified execution at site.

The reduced concrete volume and smaller member sizes also improved ease of handling, reinforcement placement, and shuttering work. These advantages make the proposed system suitable for modern highway underpass projects where economy and fast construction are important requirements.

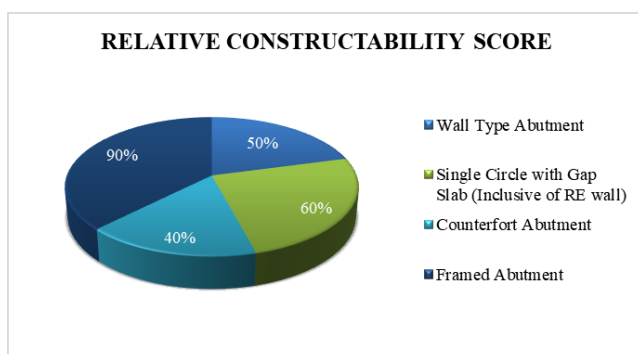


Fig. 10. Relative constructability score

CONCLUSION

Based on the analysis and design carried out in the present study, the following conclusions are drawn:

1. The proposed framed-type abutment system was found to be structurally safe under all critical loading combinations, including seismic loading conditions as per IRC provisions.
2. Stability checks confirmed satisfactory performance against sliding, overturning, and bearing failure. All factor of safety values remained within permissible limits.
3. The framed configuration reduced concrete quantity by 45.6% and excavation depth by approximately 83% compared to the conventional wall-type abutment. This reduction was primarily achieved through redistribution of earth pressure through frame action and reduction in cantilever bending demand.
4. The proposed system required lower safe bearing capacity and significantly reduced foundation depth. This reduced excavation quantity, backfill requirement, and overall construction cost.
5. The finite element analysis confirmed improved stress distribution and efficient load transfer behaviour in the framed-type configuration.
6. The mesh convergence study showed that a 0.50 m mesh size provided accurate structural response with good computational efficiency.
7. The framed-type abutment exhibited improved seismic behaviour due to lower structural mass, reduced inertia forces, and efficient redistribution of seismic forces.
8. From a construction perspective, the proposed system offered better constructability, easier execution, and reduced construction time due to compact geometry and lower excavation depth.
9. Based on structural performance, economy, and constructability, the proposed framed-type abutment can be considered a practical and efficient alternative for future highway underpass and bridge substructure projects.

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