

Soil Deformation and Lateral Pressure Ratcheting in Integral Bridges Absent from IRC Provisions

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Abstract—This study presents a comparative assessment of the structural response of integral abutment bridges, with particular emphasis on the effects of lateral earth pressure ratcheting as represented by the K^ parameter in PD 6694 1:2011. A 10 m single span integral bridge was modelled using Midas civil software with realistic material properties and boundary conditions. Two analysis cases were considered: (i) a baseline model employing conventional earth pressure assumptions, and (ii) an enhanced model implementing the K^* earth pressure coefficient to represent thermal cycle-induced densification of backfill behind the abutments. The results demonstrate significant differences in structural response, with the K^* case exhibiting increased bending moments at the deck–abutment junction and elevated shear forces along the abutment height relative to the baseline model. These findings underscore the importance of incorporating pressure ratcheting in design calculations, particularly for the assessment of structural capacity and durability over the bridge service life. The study also identifies a gap in the Indian Roads Congress (IRC) provisions concerning lateral earth pressure development for integral bridges and proposes design considerations to better account for these effects in practice. The methodology and findings provide actionable insights for bridge engineers seeking to optimize integral abutment design for structural efficiency and long-term performance.*

Index Terms— K^ , integral bridge, Thermal Earth pressure, IRC, PD 6694.*

I. INTRODUCTION

Integral bridges, characterized by monolithic construction wherein the deck is cast integrally with the abutments without expansion joints or bearings, represent a significant advancement in contemporary bridge engineering. This configuration offers well documented advantages over conventional jointed systems, including reduced maintenance, improved durability, enhanced structural continuity, and heightened resilience to seismic actions. By eliminating expansion joints—frequent sources of water ingress, debris accumulation, and subsequent

deterioration—integral bridges generally achieve superior long-term performance and service life. The construction process is often more straightforward and economical, further supporting their increasing adoption for short to medium spans globally.

Notwithstanding these benefits, integral bridges pose distinctive design challenges arising from soil–structure interaction, most notably the phenomenon of lateral earth pressure ratcheting. Unlike conventional bridges, where abutments can accommodate thermal movements independently of the superstructure, integral abutments undergo cyclic longitudinal displacements with the deck due to thermal variations. During warm periods, expansion drives the abutments against the backfill; during cold periods, contraction can create a temporary gap, which is progressively infilled by soil. Subsequent expansion phases mobilize this densified backfill, progressively increasing lateral pressures with each thermal cycle. This ratcheting mechanism leads to enhanced earth pressures that may exceed those predicted by conventional static earth pressure theories, with potential implications for structural safety and serviceability over time.

Classical earth pressure states frame this behavior. The active condition arises when the structure moves away from the retained soil, allowing lateral strain and stress reduction to a limiting state, commonly represented for cohesionless soils by Rankine's coefficient $K_a = \tan^2(45^\circ - \phi/2)$, where ϕ is the soil friction angle. Active conditions typically mobilize with small wall movements on the order of 0.001H–0.004H, where H is wall height. Conversely, the passive condition corresponds to compression of the soil mass as the structure moves toward it, with Rankine's $K_p = \tan^2(45^\circ + \phi/2)$, requiring larger movements, typically 0.02H–0.06H, to fully mobilize resistance. The at rest condition, K_0 , represents lateral stresses with negligible wall movement; for

normally consolidated soils, Jaky's expression $K_0 = 1 - \sin\phi$ is commonly adopted. While integral bridges may initially experience at rest conditions, cyclic thermal movements drive progressive densification, elevating pressures beyond K_0 and above active values, though often below fully mobilized passive resistance. This intermediate, cyclically enhanced state is explicitly addressed by the K^* approach in PD 6694 1:2011.

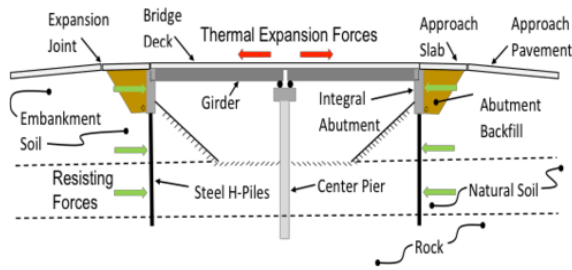


Figure 1

PD 6694 1:2011 ("Recommendations for the design of structures subject to traffic loading to BS EN 1997 1:2004") provides a methodology for estimating the increased lateral earth pressures arising behind integral abutments due to cyclic movements. The K^* parameter accounts for abutment height, thermal displacement, soil properties, and the number of thermal cycles, offering a more realistic representation than conventional earth pressure theories for integral systems. The standard outlines procedures for computing this enhanced pressure and incorporating it into design.

Accurate representation of these pressures is essential. Underestimation can precipitate excessive deformations, cracking, and potential overstress in abutments; overestimation may lead to uneconomical designs. Moreover, long term performance—encompassing structural safety and serviceability, including approach slab behavior and transition zone settlements—is governed by soil–structure interaction. Reliable predictive methods are therefore critical to achieve optimized, durable designs.

This research quantifies the differences in structural response of a 10 m single span integral bridge with and without application of the K^* earth pressure as defined in PD 6694 1:2011. Using advanced finite element analysis, the study examines bending moments, shear forces, and displacements, comparing

results from both scenarios to establish the significance of accounting for ratcheting effects and the consequences of neglecting them.

The implications for Indian practice are notable. While IRC provisions are comprehensive for conventional bridges, explicit guidance for integral abutments—particularly regarding lateral earth pressure under cyclic action—remains limited. Given the increasing adoption of integral solutions in India, this study addresses a critical gap by interpreting international approaches such as PD 6694 1:2011 in the context of Indian geotechnical and climatic conditions, and by proposing design considerations to support safe and economical implementation.

II. METHODOLOGY

Modelling Platform and Approach

A comprehensive three dimensional finite element model of a 10 m single span integral bridge was developed using Midas Civil (version v1.1 2025). The model employed shell and beam elements for the deck and abutments and spring elements to represent soil–structure interaction. The superstructure (deck slab), substructure (abutments with open foundations), and surrounding soils were modelled as an integrated system. Particular attention was given to the deck–abutment interface to ensure appropriate moment transfer consistent with integral behavior. A global coordinate system was adopted with the X axis along the bridge longitudinal direction, the Y axis transverse, and the Z axis vertical.

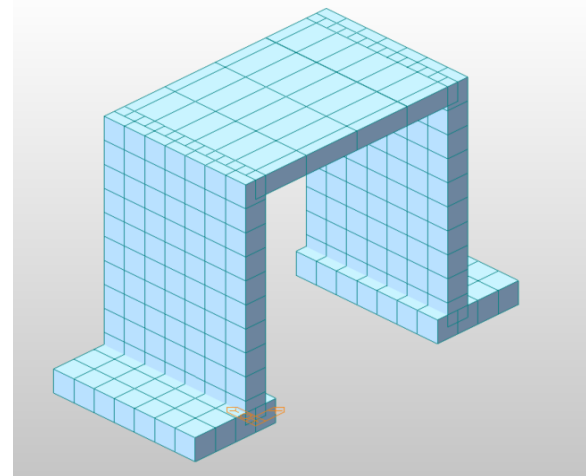


Figure 2

Bridge Geometry

The bridge model was defined by the following parameters:

- Span length: 9.0 m (center to center of abutments)
- Deck width: 8.0 m
- Deck thickness: 800 mm (constant)
- Abutment height: 7.2 m (foundation level to deck soffit)
- Abutment thickness: 1000 mm
- Toe width: 1000 mm
- Heel width: 3000 mm
- Deck–abutment connection: monolithic with full reinforcement continuity to reflect the integral configuration.

Material Properties

- Concrete: Grade C40/50; density 25 kN/m³
- Reinforcement steel: Grade Fe500 (characteristic yield strength $f_y = 500$ MPa)
- Backfill soil: unit weight 20 kN/m³; angle of internal friction $\phi = 35^\circ$
- Foundation soil: subgrade modulus 1000 kPa

Boundary Conditions

Abutment foundations were supported by vertical springs calculated to represent the stiffness of the underlying soil. Spring stiffness values were derived from foundation dimensions and the presumed soil bearing capacity to capture vertical compliance realistically.

Implementation of K^* Earth Pressure

Two analysis scenarios were undertaken to quantify ratcheting effects:

- Scenario 1: Conventional Earth Pressure

The model used standard coefficients for cohesionless backfill with $\phi = 35^\circ$:

Active earth pressure coefficient, and rest earth pressure coefficient, K_0 .

- Scenario 2: K^* Enhanced Earth Pressure

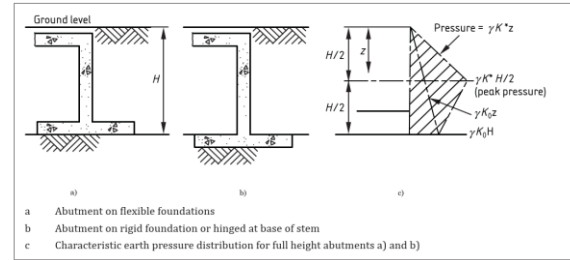


Figure 3

The K^* coefficient was implemented in accordance with PD 6694 1:2011, incorporating the influence of abutment height, thermal displacement amplitude, soil density and friction angle, and cumulative cyclic effects. The soil stiffness and lateral pressure distribution were adjusted to reflect progressive densification and pressure build up due to thermal cycling.

Loading Conditions

The analysis considered:

- Self weight
- Active earth pressure and At rest earth pressure
- K^* enhanced earth pressure (for the enhanced scenario)
- Uniform thermal load to represent seasonal temperature variation

Analysis Procedures and Output Metrics

For Scenario 1, a standard incremental analysis with constant soil properties was performed. For Scenario 2, soil stiffness parameters were progressively modified to simulate ratcheting behavior consistent with PD 6694 1:2011 guidance. For each scenario, the following response quantities were extracted:

- Effect due to soil pressure along the abutment height
- Bending moments along the deck and at the deck–abutment junction
- Shear forces within the abutments and deck

III. RESULTS

As per the above-mentioned loads applied on the frame and the results were compared for the realistic behavior.

It was noticed that the effect of K_0 and K^* provides huge difference in the result. Below are the few snaps for the most onerous/design ULS and Shear cases. Where the difference is significant.

A. Effect due to soil pressure

Effect of independently due to the earth pressure is having maximum and minimum moments of 1368KN.m /m and -453KN.m /m for the earth pressure at rest condition where maximum and minimum moments of 2035KN.m /m and -769KN.m /m noticed for the earth pressure with K^* .

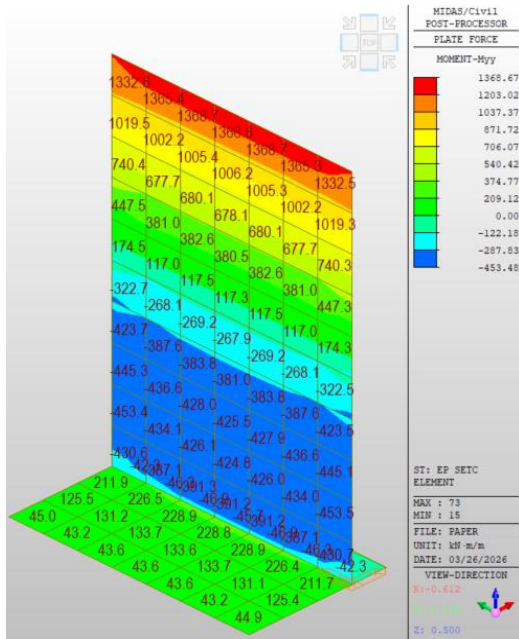


Figure 4

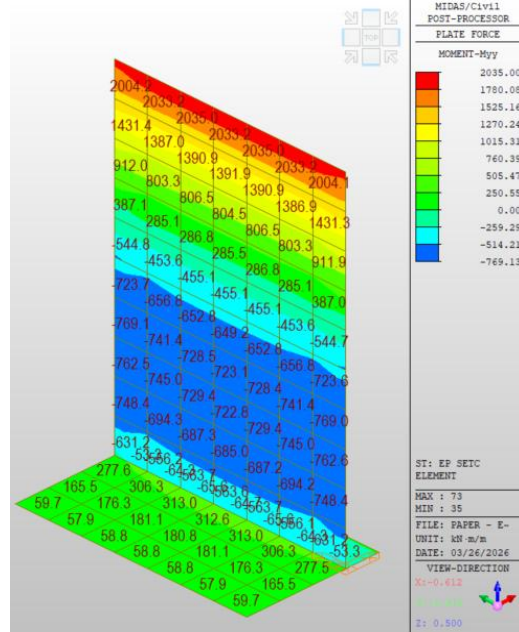


Figure 5

B. Effect on ULS moments

Considering the Euro Code load Combination the ULS design moments were derived for the deck and abutment wall for normal earth pressure and that came around maximum and minimum moments of 452KN.m and -2734KN.m for Deck where maximum and minimum moments of 3108KN.m /m and -1078KN.m /m noticed for Abutment.

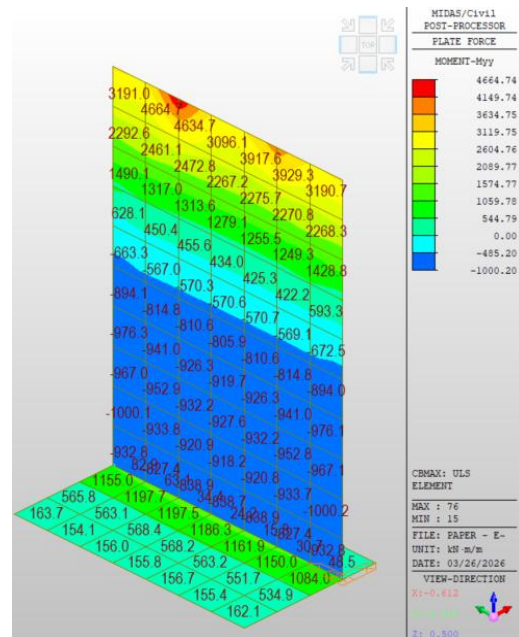


Figure 6

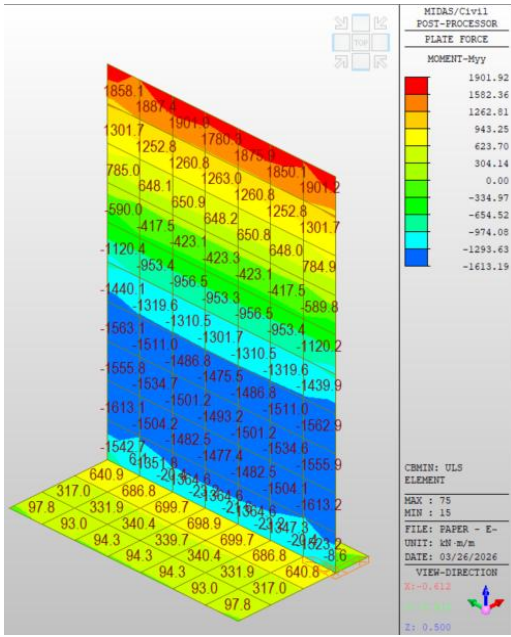


Figure 7

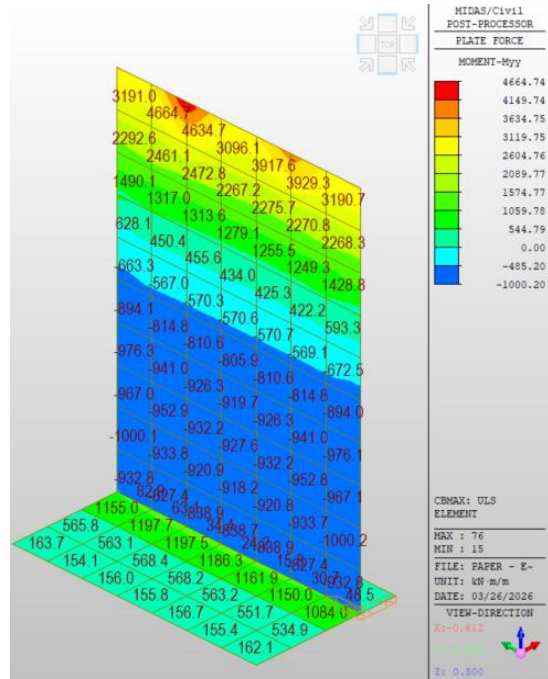


Figure 10

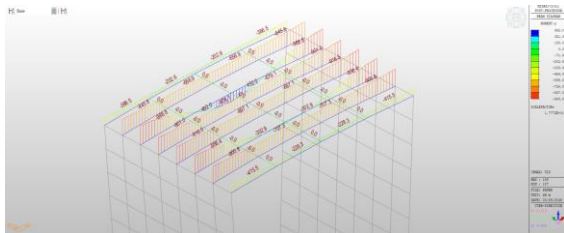


Figure 8

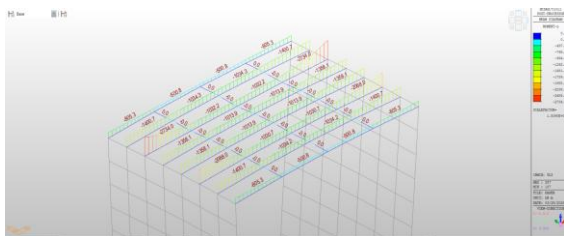


Figure 9

Considering the same Euro Code load Combination, the ULS design moments were derived for the deck and abutment wall for Thermal earth pressure and that significantly higher both end and came around maximum and minimum moments of 452KN.m and -4050KN.m for Deck where maximum and minimum moments of 4664KN.m/m and -1613KN.m/m noticed for Abutment.

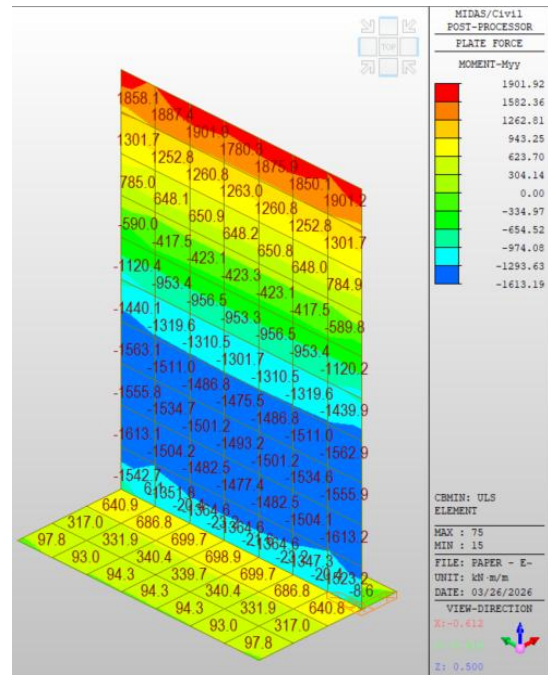


Figure 11

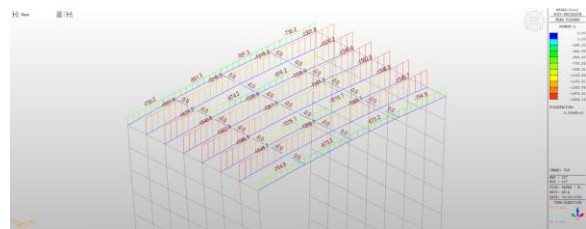


Figure 12

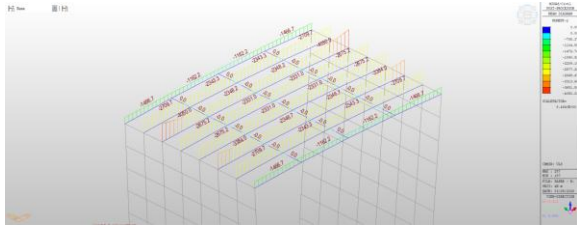


Figure 13

C. Effect on Shear force

Similar variation in the shear force can be found in both variants of the force application. Here we can find the -1386KN/m shear force in Abutment wall for the pressure at rest condition and -1937KN/m shear force for the abutment wall applied with the thermal earth pressure.

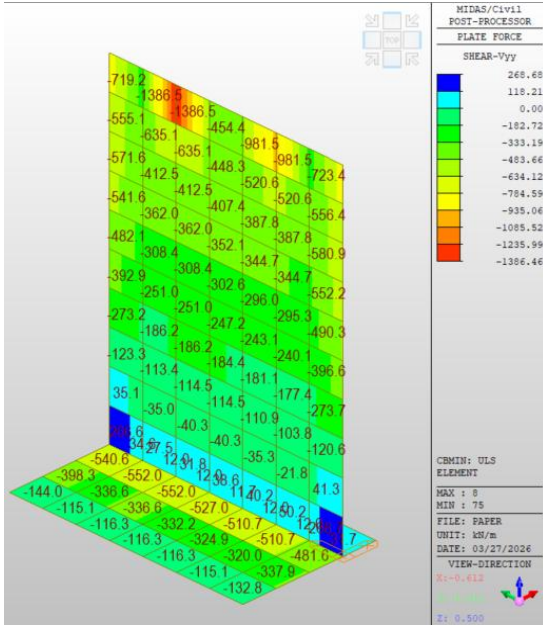


Figure 14

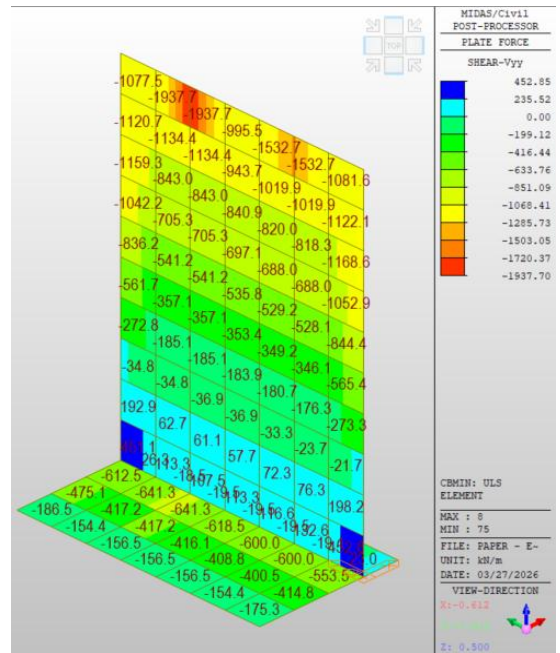


Figure 15

As per the above results, here are some comparisons which indicate that the difference is noticeable and this force needs to be carried out for the design of integral bridges.

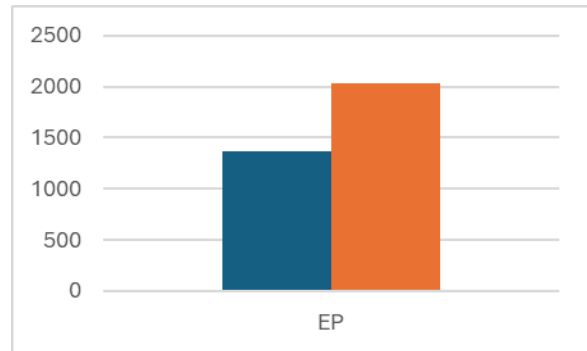


Figure 16

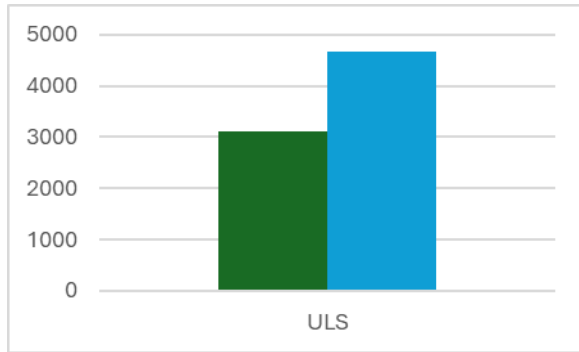


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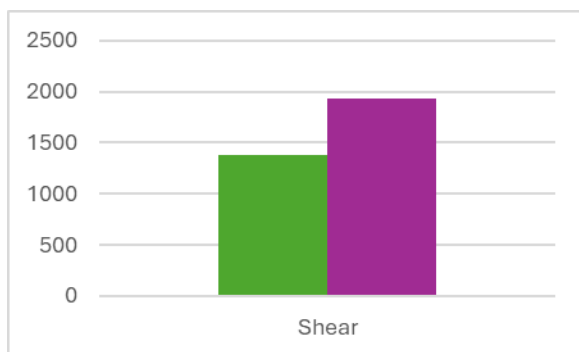


Figure 18

VI. CONCLUSION

The provision in the IRC for the integral bridge is not sufficient, in absence of the thermal ratcheting effect's criteria in IRC, effect of K^* provided in PD 6694 as per Euro code need to be considered to analyze accurately.

REFERENCES

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- [4] BS EN 1990:2002+A1:2005
- [5] BS EN 1997-1:2004+A1:2013.