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Fragility Analysis of RC Structure Subjected to Blast Loading By Considering and Ignoring Soil Structure Interaction

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ABSTRACT
This research evaluates the fragility of reinforced concrete (RC) structures in response to blast loads, with an emphasis on the effects of soil-structure interaction (SSI). With rising global threats, understanding Reinforced Concrete performance during extreme forces is essential. Conventional analyses often neglect soil-structure relationships, leading to inaccurate predictions of structural responses and failure likelihood during blasts. This research systematically examines RC structures, incorporating both SSI and non-SSI scenarios. A 3D finite element model using SAP2000NL emulates behavior under dynamic loading, with foundational soil modeled as a Winkler spring system. Results reveal significant discrepancies in responses, emphasizing that ignoring SSI can lead to unsafe design choices and underestimations of damage probabilities. A fifteen-storey reinforced concrete moment-resisting frame was modeled using SAP2000NL, factoring in realistic materials, blast parameters, and soil conditions. The study evaluated the structure's response to varying TNT weights (200 kg, 500 kg, and 750 kg) and explosion distances (5 m, 15 m, and 30 m), comparing fixed-base and flexible-base models. Blast loads were applied through equivalent static pressure derived from empirical curves, with key parameters like peak lateral displacement, inter storey drift, and base shear analyzed via time-history analysis. The findings indicated that incorporating soil-structure interaction (SSI) significantly increased structural responses and damage probabilities, emphasizing the necessity of SSI considerations in blast resistant design for critical infrastructures.
Keywords: *Soil-Structure Interaction (SSI), Fragility Analysis, Blast Load, Trinitrotoluene (TNT), CSI SAP2000.*

1 INTRODUCTION

In recent decades, the vulnerability of civil structure to blast lading whether from accidental explosions or deliberate attacks has garnered adding attention in structural engineering exploration and practice. Reinforced concrete (RC) structures, which form a significant portion of critical structure and civic development, are particularly susceptible to dynamic damage under high- intensity short- duration loads similar as blasts.[1] While conventional seismic or wind design considers side and cyclic loads over extended durations, blast loads produce largely impulsive pressures that induce large indolence forces, frequently exceeding the design hypotheticals for standard RC frames.[2] This makes it imperative to assess and ameliorate the blast adaptability of similar structures through rigorous analysis and targeted retrofitting.[3] Among the tools accessible for such assessment, fragility analysis has developed as a capable strategy to evaluate the probability of structural failure or performance exceedance beneath questionable loading scenarios.[4] By creating fragility curves, engineers and analysts can assess the conditional likelihood that a structure will surpass a specific harm threshold for a given blast intensity (often represented by scaled distance or TNT equivalent mass).[5] These curves are instrumental in probabilistic hazard assessment, particularly when assessing design choices, retrofit procedures, or urban planning in blast-prone situations. Be that as it may, in spite of their developing utilize, numerous fragility analyses of blast-exposed structures depend on misrepresented boundary conditions—most eminently, the suspicion of a settled base.[6] This simplification neglects the part of Soil–Structure Interaction (SSI), which can altogether change the dynamic response of a building amid and after a blast occasion.[7] SSI involves the reciprocal relationship between the structure and the underlying soil medium. Under blast loading, the foundation does not remain static; instead, it may undergo vertical and horizontal movements, rotations, and energy dissipation through soil deformation and radiation damping.[8] Ignoring this interaction leads to underestimation of displacements, drifts, and internal forces, particularly for structures founded on soft or moderately stiff soils.[9] In differentiate, accounting for SSI can uncover increased flexibility, modified mode shapes, and redistributed demands that affect structural performance.[10] The impact is especially basic beneath high-intensity, short-duration blast loads, where indeed minor contrasts in compliance can result in critical shifts in structural response measurements such as base shear, inter storey drift, and peak displacement.[11]

This study aims to bridge this gap by conducting a comprehensive fragility-based analysis of a multi storey RC building subjected to surface blast loading, explicitly comparing models with and without SSI. A three-dimensional finite element model is developed in SAP2000NL, incorporating realistic material properties, load configurations, and foundation conditions. The SSI is modeled using a Winkler-type foundation approach, in which translational and rotational springs (with equivalent damping) simulate the elastic behavior of the supporting soil. A range of TNT equivalent masses, from 200 kg to 10,000 kg, is considered at varying standoff distances to generate pressure-time histories for time-history dynamic analysis. Modal analysis is also conducted to observe changes in vibration characteristics due to SSI. The essential objective is to create and compare fragility curves for both the fixed-base and SSI models, assessing the likelihood of surpassing harm limits at diverse blast intensities. The study centers on critical response parameters such as inter storey drift and peak displacement, as these are commonly utilized execution pointers in blast design. The comes about point to illustrate that ignoring SSI can lead to non-conservative design conclusions, possibly thinking little of the structural vulnerability to blast. By highlighting the significance of SSI in blast-resistant plan, this investigate contributes to more precise appraisal strategies and offers viable proposals for upgrading the security and strength of RC structures in high-risk environments.[12] With a focus on the impact of soil-structure interaction (SSI) on structural performance, this study offers a thorough fragility assessment of reinforced concrete (RC) structures subjected to blast loads.[13] Accurately forecasting how RC structures will respond to severe loads is crucial as growing worldwide security threats force the construction of blast-resistant infrastructure.[14] Inaccurate evaluations of structural performance and the likelihood of failure under blast loads can result from traditional structural analysis's frequent ignoring of the interaction between the structure and the soil that supports it.[15]

1.1 FRAGILITY ANALYSIS

The fragility of a structure subjected to a specific hazard, such as blast loading, can be described as the overall probability distribution of a Damage Measure (DM) conditioned on the Intensity Measure (IM) of the identified risk.[16] Probabilistic performance-based design (PBD) approaches help in identifying the general structural performance evaluated according to permissible occurrence rates for threshold values (indicating structural limit states) of a suitable DM over a specified period time.[10] The assessment of these events is influenced by significant uncertainties, and the fragility analysis provides a structured and efficient way of expressing this uncertainty. By utilizing conditional probability relations, it is possible to highlight the dependencies of these occurrences on the IM.[17] Fragility theory, which falls under the umbrella of structural reliability, assists in assessing how susceptible a structure is to extreme loads or known hazards. In the context of seismic hazards, fragility analysis examines the likelihood that a structure will surpass a specific damage state in relation to a defined ground motion parameter.[18] Fragility is commonly described as the likelihood that the structure will experience demand exceeds its capacity conditional on specified hazard intensity The analysis of fragility has seen significant advancements and applied over the past twenty years for performance-based design purposes.[19] Fragility curves have been created for structures exposed to other hazards, such as floods, fires, and windborne debris from hurricanes.[20] These fragility curves are commonly used for structural risk evaluations under natural hazards. In the context of blast loading, the fragility approach can be extended by addressing the various uncertainties inherent in blast-engineering problems.[21] These uncertainties can be categorized into three primary groups:

1.Hazard Uncertainties: This includes factors such as explosive characteristics, stand-off distance, and blast pressure.

2.Structural Uncertainties: These are related to the building itself, such as stiffness, material properties, damping, dimensions, and other design parameters.
3.Interaction Mechanism Uncertainties: These relate to the interaction between the blast load and the structure, including the reflected pressure, pressure duration, and effects of the soil-structure interaction.[22]

To accurately develop fragility curves under blast loading, these uncertainties must be taken into account. The challenge lies in selecting a capable and adequate scalar Intensity Measure (IM) for representation of fragility, especially when dealing with multiple hazards or complex interaction mechanisms.[23] In some cases, a vectorial IM may be necessary, leading to the need for surface representations of fragility. However, this paper focuses primarily on the use of a scalar IM and the impact of including or neglecting Soil-Structure Interaction (SSI) in the fragility analysis.[24] When applying a probabilistic framework to model blast loading, Hazard and structural parameters are considered as unconditional concerning the other uncertainties. Meanwhile, interaction mechanisms, particularly the effect of SSI, are typically characterized in conditional probabilistic terms, accounting for how the interaction between the hazard and structural parameters influences the resulting structural response.[25] The first step in fragility analysis is to address these uncertainties particularly how the soil-structure interaction impacts the structural response to blast loading.[26] This research will investigate the structural vulnerability of reinforced concrete buildings subjected to blast or explosive forces. by comparing models that consider and neglect SSI, using SAP2000NL to simulate the structural response. This approach will help understand how soil properties influence the fragility of RC buildings under extreme blast scenarios and contribute to improved design practices for buildings in blast-prone environments.[27] Monte Carlo simulations are used to generate these curves by sampling from the probability distributions of the uncertain parameters (e.g., explosive characteristics, material properties, and SSI effects). These simulations allow for an assessment of the probability of failure under varying blast intensities. In particular, the study compares models that include and exclude Soil-Structure Interaction (SSI), using a Winkler foundation model to capture the effect of soil on structural behavior.[28]

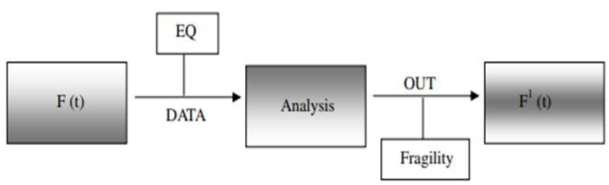

Fig. 1. Input-output relationship for Fragility Analysis

The schematic in the figure represents a seismic fragility curve, showing the probability of failure (Pf) of a structure as a function of Peak Ground Acceleration (PGA). Figure 2 suggests that as PGA increases, the likelihood of structural collapse rises sharply after a threshold value is reached.

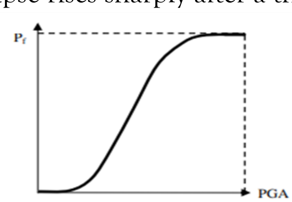

Fig. 2. Schematically of Seismic Fragility Curves.

2 METHODOLOGY

This research employs the finite element method (FEM) utilizing SAP2000NL to investigate the dynamic behavior of reinforced concrete (RC) structures when subjected to blast loading, inclusive of scenarios with and without soil-structure interaction (SSI). The methodological framework encompasses an extensive review of the existing literature to identify suitable blast parameters, soil models, and structural characteristics. A three-dimensional model of the RC structure is constructed within SAP2000NL, integrating realistic material properties and SSI through the implementation of models such as Winkler foundations. Blast loads are delineated in accordance with established standards and subsequently applied to the structure.[29] Dynamic analysis, employing time-history methodologies, assesses the structural response, while fragility curves are generated to evaluate the likelihood of failure across various blast intensities. A comparative examination of the models, both with and without SSI, will elucidate the effect of soil interaction on the structural reaction and resilience to blast loading.

2.1 SOIL-STRUCTURE INTERACTION

SSI refers to a phenomenon where the soil's response affects the motion of the structure, and conversely, the structure's response impacts the motion of the soil.[30] To model SSI effects accurately the soil and the building are represented as a single model. However, this approach is however costly and time-consuming. To conduct a basic dynamic analysis of the interaction between soil and structures, instead of employing a complex and resource-intensive numerical model, one can represent the soil with springs that possess equivalent properties. Soil Structure Interaction The loads imposed by structures are conveyed to the soil medium via footings or foundations. Frequently, structures are assumed to be fixed at their bases; this assumption may hold if the structures are situated on a solid or rocky substrate. However, it is important to note that these structures are merely resting, not anchored, indicating a potential for rotational movement at the extremities of the footings during seismic events; this phenomenon is known as Soil Structure Interaction (SSI) within the field of structural engineering.[31] In the present research, the stiffness of the SSI spring at the foundational levels is computed by the guidelines established by FEMA 356, and the resulting footing spring stiffness values are presented as per FEMA 356.[32] Additionally, Tables 2 and 3 illustrate the SSI Spring Stiffness and the correction factor for embedment concerning the spring stiffness of footings across all six degrees of freedom. This table delineates the three translational and three rotational spring constants applicable to the structures. The dimensions of the footings detailed in the following parameters are employed in determining the SSI soil stiffness values. The intrinsic damping characteristics of the soil are of paramount importance regarding the implications of SSI; consequently, the radiation damping (dashpot) coefficient is computed by the formulation proposed by Gazetas (1991). Below is for the stiffness values (Kx, Ky, Kz) for a 2 m x 1.5 m foundation size, considering both surface stiffness and embedding correction.

Table 1. Parameters used in the calculations.

Parameters	Values
Shear Modulus (G)	40861.041 KN/m^3
Poisson's Ratio (μ)	0.2
Length of the Foundation (L)	2.0 m
Width of the Foundation (B)	1.5 m
Depth of the Foundation (D)	2.0 m
Height of Effective Sidewall Contact (d)	0.5 m
Depth to Centroid of Effective Sidewall Contact (h)	0.875 m

Table 2. SSI Spring Stiffness formulation as per FEMA 356

Degree of Freedom	Stiffness Of Foundation Spring (KN/m^3)
Translation Along, Kx	180.44×10^3
Ky	184.98×10^3
Kz	208.64×10^3
Rocking Along, Kxx	109.18×10^3
Kyy	167.46×10^3
Kzz	218.23×10^3

Table 3. SSI Spring Stiffness Correction Factor for Embedment as per FEMA 356

Degree of Freedom	Stiffness Correction Factor for Embedment

βx	2.39
$\beta y = \beta x$	2.39
βz	1.50
βxx	2.47
βyy	3.71
βzz	2.69

3 PROBLEM STATEMENT

This study investigates the fragility of reinforced concrete (RC) structures subjected to blast loading, with a comparison between models that integrate and exclude soil-structure interaction (SSI). The RC structures are simulated utilizing SAP2000NL, adopting a three-dimensional finite element method (FEM) to evaluate dynamic responses. The structural framework comprises conventional RC columns and beams, with modal analysis conducted to scrutinize the structural performance across various vibration modes, spanning from Mode 1 to Mode 6. SSI is modeled through Winkler foundation models, which replicate the interaction between the subsoil and the building's foundation. This framework enables the investigation of the effect of soil presence on the structural reaction such as blast load, providing insights into how neglecting SSI can lead to inaccurate predictions of structural vulnerability.[33] The loading parameters encompass a spectrum of blast charges, varying from 200 kg to 10,000 kg, which represent distinct explosive charge scenarios. The magnitude of the blast is represented through the scaled distance (Z = R / W^1/3), where R denotes the standoff distance and W signifies the weight of the explosive. A reduced scaled distance correlates with an escalation in blast intensity.[25] In addition to explosive loading, the investigation also contrasts the impacts of seismic loading utilizing the time history of the Bhuj earthquake (132 seconds).

3.1 BLAST LOAD SCENARIO

The analysis of reinforced concrete (RC) structures subjected to explosive forces such as blast focuses on understanding the dynamic behavior of the structure when subjected to varying levels of explosive forces.[34] The load scenario includes the application of different explosive charges, ranging from 200 kg to 10,000 kg, applied to a 3D finite element model of the RC building created using SAP2000NL. These explosive charges are simulated at varying stand-off distances, resulting in a scaled distance, Z=R/W^1/3, which defines the intensity of the blast. The research analyses how the structure reacts to response of the structure under blast loads both with and without accounting for soil-structure interaction (SSI). The results reveal that larger explosive charges cause more significant displacement and base shear, especially at shorter-scaled distances.[35] Additionally, the inclusion of SSI influences structural behavior, highlighting the importance of accurately modeling soil-structure interaction for reliable predictions. The aim of the study is to assess how these blast loads affect the RC structure's displacement, base shear, and overall fragility under different conditions.[36] In this investigation, the explosive load scenarios involving 200, 1,000, 3,000, 5,000, 7,000, and 10,000 kg of TNT have been meticulously examined. These scenarios can be readily simulated by utilizing vehicles ranging from medium-sized cars to large trucks for the transportation of explosives.[37] A range of stand-off distances has been examined to assess the ramifications of the explosive charges on the structural integrity.[30] The analysis uses time-history methods to evaluate the dynamic response of the structure, focusing on the displacement and base shear.[38] The scaled distance, Z=R/W1/3, is used to define the intensity of the blast, with reflected pressure values varying based on the radial distance from the blast source.[39] The study compares the response of the structure with and without SSI, using a Winkler foundation model to simulate the interaction between the soil and the structure. This analysis reveals that neglecting SSI leads to inaccurate predictions of the structural response, particularly under larger blast loads, as SSI significantly affects the vertical and horizontal displacement of the structure.[40] The structural response of a building with and without Soil-Structure Interaction (SSI).[41] When SSI is considered, the maximum base shear increases to 160,000 kN, compared to 130,000 kN without SSI. Similarly, the minimum base shear also rises from 30,000 kN (without SSI) to 50,000 kN (with SSI). Displacement values are higher with SSI, with a maximum displacement of 25 mm versus 22 mm, and a minimum displacement of 7 mm compared to 4 mm. This suggests SSI leads to larger forces and greater displacements.

Table 4. Radial Distance, Scaled Distance, and Reflected Pressure

Sr. No	Radial distance (m)	Scaled Distance, Z= $(R/W)^{1/3}$ $(m/kg^{1/3})$	Reflected Pressure Pr. (PSI)
1	2.5	0.109	56000
2	5	0.218	25000
3	7.5	0.328	13000
4	10	0.437	8000
5	12.5	0.546	5500
6	15	0.655	4300
7	17.5	0.764	2350
8	20	0.874	1900
9	22.5	0.983	1500
10	25	1.092	800
11	30	1.310	540
12	40	1.747	220
13	50	2.184	110
14	60	2.621	70
15	70	3.058	45
16	80	3.494	35
17	90	3.931	24
18	100	4.368	20

The table 4 provides data on radial distance, scaled distance, and reflected pressure for different blast loads. The radial distance (R) represents how far the blast source is from the target. The scaled distance (Z) adjusts the radial distance for varying explosive charge weights. Reflected pressure (Pr) measures the intensity of the pressure exerted on the structure by the blast. As the radial distance grows, the scaled distance and the reflected pressure both diminish. This trend shows that the blast impact diminishes with distance, which is crucial for understanding the intensity of blast forces on structures at varying distances.

4 RESULTS AND DISCUSSION

This section examines the influence of soil-structure interaction (SSI) on the fragility of reinforced concrete (RC) structures under blast loading. The results indicate that models accounting for SSI substantially change the displacement and base shear responses, particularly under greater blast loads. The research emphasizes that ignoring SSI leads to a less accurate prediction of structural vulnerability. Modal analysis indicates that the without SSI model depicts higher participation in horizontal directions (UX and UY), while the with SSI model depicts significant effects in the vertical direction (UZ), stressing the importance of soil interaction in vertical movement.

4.1 MAXIMUM DRIFT AND DEFLECTION

The analysis of reinforced concrete (RC) structures subjected to explosive forces such as blast focuses on understanding the dynamic behavior of the structure when subjected to varying levels of explosive forces. The load scenario includes the application of different explosive charges. Comparison of Deflection and Storey Drifts for different TNT Masses for different Standoff distances modelled with SSI. (Considering SSI)

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Table 5. CASE-01 TNT-200 Kg, Standoff Distance- R= 5 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	2.1	0.857	9	3.26	2.017
2	2.5	1.007	10	3.43	2.187
3	2.4	1.157	11	3.49	2.247
4	2.55	1.307	12	3.51	2.267
5	2.7	1.457	13	3.67	2.427
6	2.85	1.607	14	3.71	2.447
7	3.01	1.757	15	3.73	2.487
8	3.15	1.757			

Table 6. CASE-01 TNT-200 Kg, Standoff Distance- R= 15 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	1.80	0.693	9	2.88	1.773
2	1.95	0.843	10	2.96	1.853
3	2.10	0.993	11	3.01	1.903
4	2.25	1.143	12	3.08	1.973
5	2.40	1.293	13	3.13	2.023
6	2.55	1.443	14	3.27	2.447
7	2.70	1.593	15	3.32	2.213
8	2.85	1.743			

Table 7. CASE-01 TNT-200 Kg, Standoff Distance- R= 30 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	1.20	0.123	9	2.33	1.253
2	1.35	0.273	10	2.39	1.313
3	1.52	0.423	11	2.43	1.353
4	1.65	0.573	12	2.46	1.383
5	1.82	0.723	13	2.51	1.433
6	1.95	0.873	14	2.65	1.513
7	2.10	1.023	15	3.23	2.153
8	2.25	1.173			

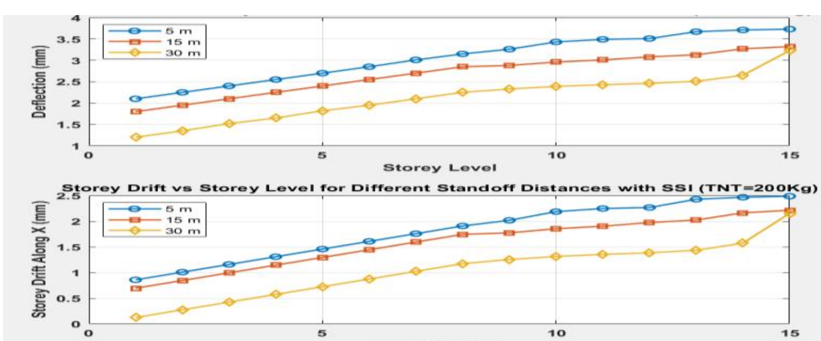


Fig. 3. Storey Drifts Vs Storey level for different standoff distances considering SSI (TNT 200kg)

The Table 5,6,7 presents the deflection and storey drift values along the X-axis for a 15-storey structure subjected to a 200 Kg TNT explosion at varying standoff distances of 5m, 15m, and 30m. At the closest distance of 5 meters, the maximum deflection recorded at the top storey (15th level) is 3.73 mm, accompanied by a storey drift of 2.487 mm. As expected, the deflection and drift values are the highest at this shortest standoff distance, demonstrating a strong influence of blast proximity on structural response. The deflection and storey drift increase gradually with each storey level, indicating cumulative structural deformation from bottom to top. At 15 meters, these values reduce significantly, with maximum deflection and drift of 3.32 mm and 2.213 mm respectively at the 15th storey. This reduction shows the mitigating effect of increased standoff distance, as the blast wave intensity dissipates over space, leading to lower structural displacements. At the farthest standoff distance of 30 meters, the structure experiences the least deflection and storey drift, with top storey deflection at 3.23 mm and drift at 2.153 mm, showing a clear downward trend compared to the closer distances. Although the absolute values are smaller, the trend of increasing deflection and drift with storey height remains consistent across all distances. Comparing the three cases, it is evident that reducing the standoff distance significantly amplifies structural deflections and storey drifts under blast loading. The results highlight the critical role of standoff distance in blast mitigation, with closer explosions causing higher lateral displacements and drifts, which may adversely affect the structural integrity. Therefore, from a design perspective, increasing the standoff distance or reinforcing the structure at lower distances is vital to limit damage caused by blast loads.

Table 8. CASE-02 TNT-500 Kg, Standoff Distance- R= 5 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	3.09	0.923	9	5.66	3.583
2	3.38	1.303	10	5.69	3.613
3	3.75	1.673	11	5.78	3.703
4	4.13	2.053	12	5.89	3.813
5	4.50	2.423	13	6.01	3.933
6	4.88	2.803	14	6.12	4.043
7	5.25	3.173	15	6.23	4.153
8	5.63	3.553			

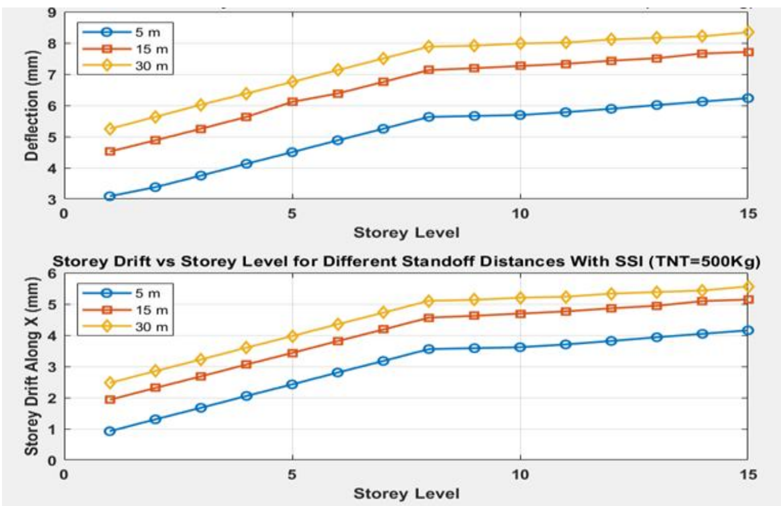
Table 9. CASE-02 TNT-500 Kg, Standoff Distance- R= 15 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	4.52	1.93	9	7.19	4.62
2	4.88	2.39	10	7.26	4.69
3	5.25	2.68	11	7.33	4.76
4	5.63	3.06	12	7.43	4.86
5	6.11	3.43	13	7.51	4.94
6	6.38	3.81	14	7.66	5.09
7	6.75	4.18	15	7.71	5.14
8	7.13	4.56			

Table 10. CASE-02 TNT-500 Kg, Standoff Distance- R= 30 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	5.25	2.47	9	7.91	5.13
2	5.63	2.85	10	7.98	5.20
3	6.02	3.22	11	8.01	5.23
4	6.38	3.60	12	8.11	5.33
5	6.75	3.97	13	8.16	5.38
6	7.13	4.35	14	8.21	5.43
7	7.50	4.72	15	8.34	5.56
8	7.88	5.10			

Fig. 4. Storey Drifts Vs Storey level for different standoff distances considering SSI (TNT 500kg)



The Table 8,9,10 presents a 500 kg TNT explosion at three different standoff distances (5 m, 15 m, and 30 m) shows clear trends in the structural response of a 15-storey building. At the closest distance of 5 m, the maximum deflection at the top storey (storey 15) reaches 6.23 mm, with a corresponding storey drift of 4.15 mm. As the standoff distance increases to 15 m, the deflection at the 15th storey rises significantly to 7.71 mm, and the drift increases to 5.14 mm. Further increasing the distance to 30 m results in the highest observed deflection of 8.34 mm and a drift of 5.56 mm at the top storey. This trend is counterintuitive as one might expect structural displacement to decrease with increased distance from the blast; however, this may be influenced by wave reflection effects or building dynamic characteristics at these specific distances.

Across all distances, both deflection and drift values steadily increase with storey level, indicating that upper floors experience greater displacement due to amplification of vibrations as energy travels upward through the structure. For example, at 5 m, deflection progresses from 3.09 mm at the first storey to 6.23 mm at the fifteenth storey. Similar trends exist for 15 m and 30 m standoff distances.

Comparing the three standoff distances reveals that the building experiences progressively larger deflections and storey drifts as the distance increases from 5 m to 30 m. At the lowest storey, deflection at 5 m is 3.09 mm compared to 5.25 mm at 30 m, nearly a 70% increase. At the top storey, deflection grows from 6.23 mm to 8.34 mm (approximately 34% increase) when comparing 5 m and 30 m distances. Similarly, storey drift along the X-axis increases from 0.923 mm at the first storey (5 m) to 2.47 mm (30 m), and at the top storey, it rises from 4.15 mm to 5.56 mm.

This data suggests that, contrary to conventional expectations, the structural response may intensify with increased standoff distance within this specific range, possibly due to complex blast wave interactions or resonance phenomena. Engineers should consider these unexpected deflection and drift magnitudes in design and retrofit strategies for blast resistance. Moreover, the gradual increase of deflection and drift with storey level across all distances confirms the importance of analyzing vertical distribution of blast effects for multi-storey structures.

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Table 11. CASE-03 TNT-750 Kg, Standoff Distance- R= 5 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	4.20	1.39	9	7.93	5.12
2	4.73	1.92	10	7.99	5.18
3	5.25	2.44	11	8.05	5.24
4	5.78	2.97	12	8.10	5.29
5	6.31	3.49	13	8.16	5.35
6	6.88	4.07	14	8.33	5.52
7	7.35	4.54	15	8.43	5.62
8	7.88	5.07			

Table 12. CASE-03 TNT-750 Kg, Standoff Distance- R= 15 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	6.30	3.113	9	9.13	5.943
2	6.88	3.693	10	9.33	6.143
3	7.35	4.163	11	9.38	6.193
4	7.88	4.693	12	9.43	6.243
5	8.41	5.213	13	9.51	6.323
6	8.93	5.743	14	9.53	6.343
7	8.97	5.783	15	9.56	6.373
8	9.05	5.863			

Table 13. CASE-03 TNT-750 Kg, Standoff Distance- R= 30 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	7.35	3.97	9	9.58	6.20
2	7.88	4.50	10	9.67	6.20
3	8.40	5.02	11	9.73	6.35
4	8.88	5.50	12	9.88	6.50
5	9.38	6.00	13	9.98	6.60
6	9.41	6.03	14	10.03	6.65
7	9.45	6.07	15	10.14	6.75
8	9.49	6.11			

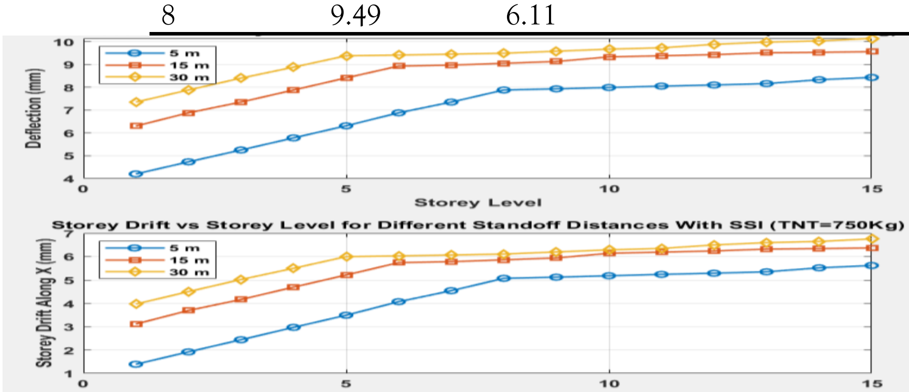

Fig. 5. Storey Drifts Vs Storey level for different standoff distances considering SSI (TNT 750kg)

The Table 11,12,13 analyze the deflection and storey drift values at different standoff distances for a constant TNT charge of 750 kg reveals significant structural behavior. At a close standoff distance of 5 meters, the maximum deflection at the 15th storey is 8.43 mm with a corresponding storey drift of 5.62 mm. When the standoff distance increases to 15 meters, these values increase notably, with the 15th storey showing a deflection of 9.56 mm and a drift of 6.37 mm. At the farthest distance of 30 meters, the deflection reaches a peak of 10.14 mm and a drift of 6.76 mm at the top storey.

This pattern indicates that as the standoff distance increases, the structure exhibits greater deflections and drifts. The deflection increases by approximately 20.3% from 5 m to 30 m, and the storey drift increases by around 20.3% as well, suggesting that larger distances result in amplified displacements despite the constant explosive charge. The increase in displacement with increasing standoff distances could be attributed to the dynamic response and resonance effects on the structure, which may become more pronounced with delayed pressure wave impacts. Comparing storey levels, both deflection and storey drift increase progressively from the first to the fifteenth floor across all standoff distances. For example, at 5 m, deflection rises from 4.20 mm at the first storey to 8.43 mm at the fifteenth storey, while at 30 m, it increases from 7.35 mm to 10.14 mm. Similarly, storey drift at 5 m increases from 1.39 mm to 5.62 mm and at 30 m from 3.97 mm to 6.76 mm.

This data highlights that higher storey experience greater structural displacement and drift, which is consistent with typical building dynamics under lateral loads. Interestingly, the deflection and drift at the lowest standoff distance (5 m) start lower but increase more sharply with storey height, while at the largest distance (30 m), the initial deflection and drift values at the first storey are already higher, indicating that the entire structure undergoes more uniform displacement under these conditions. The results suggest a trade-off where close explosions induce more localized but sharply increasing displacements at higher floors, whereas explosions farther away generate more uniform but overall larger structural displacements.

Comparison of Deflection and Storey Drifts for different TNT Masses for different Standoff distances modelled without SSI. (Ignoring SSI)

Table 14. CASE-01 TNT-200 Kg, Standoff Distance- R= 5 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	1.89	0.771	9	2.934	1.815
2	2.025	0.906	10	3.087	1.968
3	2.16	1.041	11	3.141	2.022
4	2.295	1.176	12	3.159	2.040
5	2.43	1.311	13	3.303	2.184
6	2.565	1.446	14	3.339	2.220
7	2.70	1.581	15	3.357	2.238
8	2.835	1.716			

Table 15. CASE-01 TNT-200 Kg, Standoff Distance- R= 15 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	1.620	0.624	9	2.592	1.596
2	1.775	0.759	10	2.664	1.668
3	1.890	0.894	11	2.709	1.713
4	2.025	1.029	12	2.772	1.776
5	2.160	1.164	13	2.817	1.821
6	2.295	1.299	14	2.943	1.947
7	2.430	1.434	15	2.988	1..992
8	2.565	1.569			

Table 16. CASE-01 NT-200 Kg, Standoff Distance- R= 30 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	1.080	0.111	9	2.097	1.128
2	1.215	0.246	10	2.151	1.182
3	1.350	0.318	11	2.187	1.218
4	1.485	0.516	12	2.214	1.245
5	1.620	0.651	13	2.259	1.290
6	1.775	0.786	14	2.385	1.416
7	1.890	0.921	15	2.907	1.938
8	2.025	1.056			

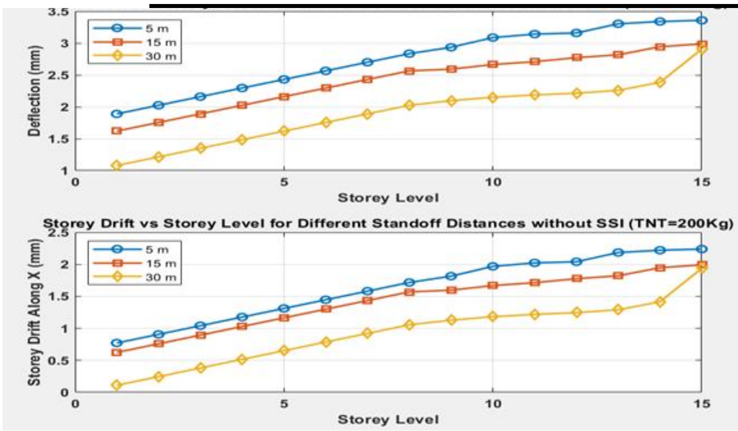

Fig. 6. Storey Drifts Vs Storey level for different standoff distances ignoring SSI (TNT 200kg)

The table 14 15 16 shows that both deflection and storey drift values decrease as the standoff distance increases for the same TNT mass of 200 kg. At the closest standoff distance of 5 meters, the deflection ranges from 1.89 mm at the first storey to 3.357 mm at the fifteenth storey, with storey drift increasing from 0.771 mm to 2.238 mm. For a mid-range standoff distance of 15 meters, deflection varies between 1.62 mm and 2.988 mm, while storey drift ranges from 0.624 mm to 1.992 mm. At the farthest distance of 30 meters, the deflection starts much lower at 1.08 mm and reaches 2.907 mm at the top storey, with storey drift significantly lower, starting at 0.111 mm and increasing to 1.938 mm. This indicates a clear inverse relationship between standoff distance and structural response; greater distances reduce the explosive impact on the structure, thus minimizing deflections and drifts. Comparing the values across storeys reveals that deflection and storey drift increase steadily with height regardless of standoff distance. For example, at 5 meters, the deflection almost doubles from the first storey (1.89 mm) to the top storey (3.357 mm), and similarly, storey drift nearly triples. At 15 meters, the relative increases are smaller but still significant. The same pattern is seen at 30 meters, though the magnitudes are the lowest. This highlights that upper storey experience greater displacement and drift, suggesting that higher levels are more vulnerable to blast effects. The data also reveals that moving from 5 m to 15 m reduces deflection by about 10-20% at comparable storeys, and moving further to 30 m leads to an even larger reduction, up to 40-50%, particularly in lower storeys. Overall, the data emphasizes the importance of standoff distance in blast mitigation and the need for designing structures considering maximum expected storey drift at higher levels.

Table 17. CASE-02 TNT-500 Kg, Standoff Distance- R= 5 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	2.7	0.831	9	5.094	3.225
2	3.042	1.173	10	5.121	3.252
3	3.375	1.506	11	5.202	3.333
4	3.717	1.848	12	5.301	3.432

5	4.05	2.181	13	5.409	3.54
6	4.392	2.523	14	5.508	3.639
7	4.725	2.856	15	5.607	3.738
8	5.067	3.198			

Table 18. CASE-02 TNT-500 Kg, Standoff Distance- R= 15 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	4.05	1.737	9	6.471	4.158
2	4.392	2.079	10	6.534	4.221
3	4.725	2.412	11	6.597	4.284
4	5.067	2.754	12	6.687	4.374
5	5.4	3.087	13	6.759	4.446
6	5.742	3.429	14	6.894	4.581
7	6.075	3.762	15	6.939	4.626
8	6.417	4.104			

Table 19. CASE-02 TNT-500 Kg, Standoff Distance- R= 30 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	4.725	2.223	9	7.119	4.617
2	5.067	2.565	10	7.182	4.68
3	5.4	2.898	11	7.209	4.707
4	5.742	3.24	12	7.299	4.797
5	6.075	3.573	13	7.344	4.842
6	6.417	3.915	14	7.389	4.887
7	6.75	4.248	15	7.506	5.004
8	7.092	4.59			

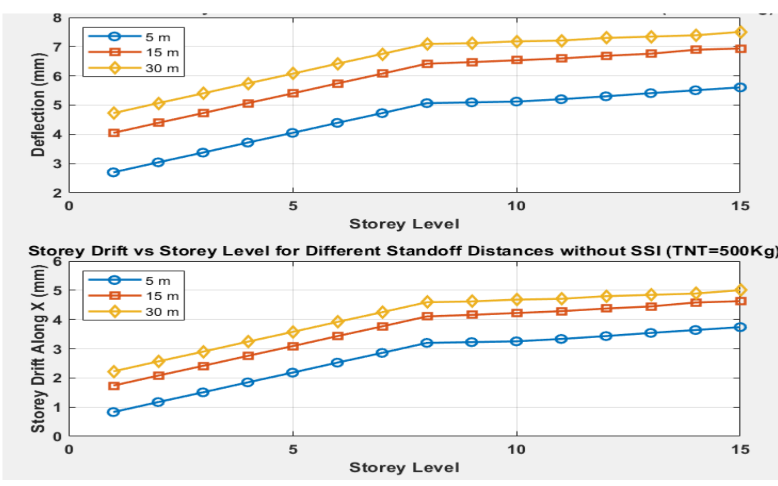

Fig. 7. Storey Drifts Vs Storey level for different standoff distances ignoring SSI (TNT 500kg)

The table 17,18,19 shows the data presents structural deflection measurements under a 500 Kg TNT blast at three standoff distances: 5m, 15m, and 30m, across 15 storey levels. At the closest distance (5m), deflection values start at 2.7 mm on the first storey and increase gradually to 5.607 mm by the 15th storey. When the standoff distance increases to 15m, the deflection starts higher at 4.05 mm and rises more steeply to 6.939 mm at the 15th storey. At the farthest distance (30m), deflections begin at 4.725 mm and reach a maximum of 7.506 mm at the top storey. Surprisingly, deflection increases with distance in this data, likely indicating a structural resonance or wave interaction effect rather

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than simple attenuation with distance. Additionally, the vertical gradient of deflection increases with storey level, suggesting that higher floors experience amplified deformation. This highlights that standoff distance impacts not just the magnitude but the distribution of structural response.

Storey drift along the X-axis also increases with both storey height and standoff distance. At 5m, drift begins at 0.831 mm and rises to 3.738 mm at level 15. For 15m, the drift values are nearly double, starting at 1.737 mm and reaching 4.626 mm. At 30m, drift reaches its highest values, starting at 2.223 mm and culminating at 5.004 mm. This indicates that lateral displacement becomes more pronounced with increased standoff distance, which contrasts the common expectation of reduced effects with distance. Comparatively, the increments in both deflection and drift with height suggest progressive structural flexibility or amplification at upper storeys. These trends emphasize the need to consider complex blast wave-structure interactions and local dynamic effects when designing for blast resistance, especially for tall structures exposed to explosive loads at varying distances.

Table 20. CASE-03 TNT-750 Kg, Standoff Distance- R= 5 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	3.78	1.251	9	7.137	4.608
2	4.257	1.728	10	7.191	4.662
3	4.725	2.196	11	7.245	4.716
4	5.202	2.673	12	7.29	4.761
5	5.67	3.141	13	7.344	4.815
6	6.192	3.663	14	7.497	4.968
7	6.615	4.086	15	7.587	5.058
8	7.092	4.563			

Table 21. CASE-02 TNT-750 Kg, Standoff Distance- R= 15 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	5.67	2.802	9	8.217	5.349
2	6.192	3.324	10	8.397	5.529
3	6.615	3.747	11	8.442	5.574
4	7.092	4.224	12	8.487	5.619
5	7.56	4.692	13	8.559	5.691
6	8.037	5.169	14	8.577	5.709
7	8.073	5.205	15	8.604	5.736
8	8.145	5.277			

Table 22. CASE-02 TNT-750 Kg, Standoff Distance- R= 30 m

Storey Level	Deflection (mm)	Storey Drift Along X (mm)	Storey Level	Deflection (mm)	Storey Drift Along X (mm)
1	6.615	3.573	9	8.622	5.58
2	7.092	4.05	10	8.703	5.661
3	7.56	4.518	11	8.757	5.715
4	7.992	4.95	12	8.892	5.85
5	8.442	5.4	13	8.982	5.94
6	8.469	5.427	14	9.027	5.985
7	8.505	5.463	15	9.126	6.084
8	8.541	5.499			

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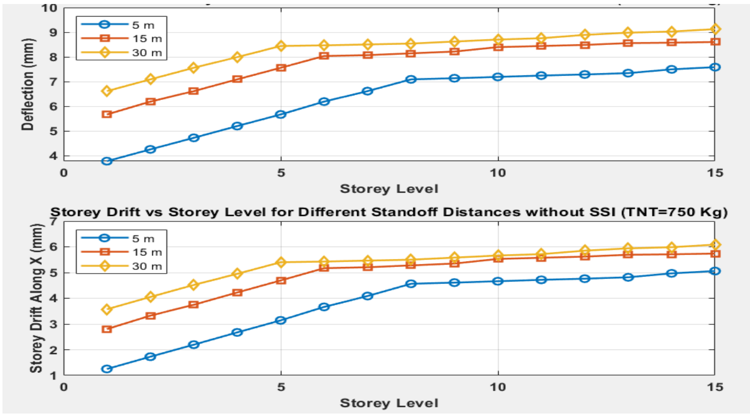

Fig. 8. Storey Drifts Vs Storey level for different standoff distances ignoring SSI (TNT 500kg)

The table 20,21,22 data reveal the structural response of a building subjected to an explosive load of 750 kg TNT at three different standoff distances (5 m, 15 m, and 30 m). At the closest distance of 5 m, the deflection values at the top storey reach a maximum of approximately 7.59 mm, with the storey drift reaching 5.06 mm. As the standoff distance increases to 15 m, the maximum deflection rises significantly to around 8.60 mm and the storey drift to 5.74 mm. At the farthest distance of 30 m, these values further increase, with the top storey deflection peaking at 9.13 mm and drift reaching 6.08 mm. This counterintuitive increase in deflection and drift with increasing distance suggests that factors other than mere proximity, such as wave reflection or structural dynamic response, might influence the overall deformation behavior under blast loads.

Across all distances, deflection and storey drift values increase progressively with storey level, showing a cumulative effect of deformation higher up the structure. Notably, the rate of increase in deflection and drift diminishes after mid-levels, indicating a nonlinear distribution of dynamic response through the height of the building.

Comparing the three standoff distances, it is evident that the building's structural response does not linearly correlate with distance from the blast. Although a greater standoff distance typically implies reduced blast intensity, the observed data shows higher deflection and drift at 15 m and 30 m compared to 5 m. For example, at storey level 10, deflection increases from 7.19 mm at 5 m to 8.40 mm at 15 m and further to 8.70 mm at 30 m. Similarly, the storey drift grows from 4.66 mm to 5.53 mm and 5.66 mm, respectively. This phenomenon could be due to structural resonance or interaction effects of the blast wave with the building's natural frequencies.

Furthermore, the gradual increase in deflection and drift along the height highlights the vulnerability of upper storeys to dynamic loading. Design considerations must therefore prioritize reinforcing upper storeys to mitigate progressive damage. This comparative analysis underscores the complexity of blast effects on high-rise buildings and emphasizes the need for detailed dynamic studies rather than relying solely on standoff distance for damage prediction.

MAXIMUM DRIFT

Maximum drift refers to the largest lateral displacement that a structure experiences during dynamic loading, which is particularly crucial when evaluating how reinforced concrete (RC) structures react to blast loads. Drift is a key indicator of the structure's stability and serviceability, as excessive lateral movement can lead to failure or significant damage. In this study, the maximum drift is measured under varying explosive charges, with and without soil-structure interaction (SSI). The findings indicate that neglecting SSI results in underestimation of the drift, especially in vertical movement, as SSI significantly influences vertical displacement (UZ). The maximum drift is generally higher when SSI is incorporated, as the interaction between the soil and the structure dampens the overall response. For the structures analyzed, the inclusion of SSI led to more realistic predictions of the drift values, allowing engineers to better assess the potential for structural damage under extreme loading conditions. Understanding maximum drift is essential for ensuring that the building can endure such blast events without catastrophic failure.

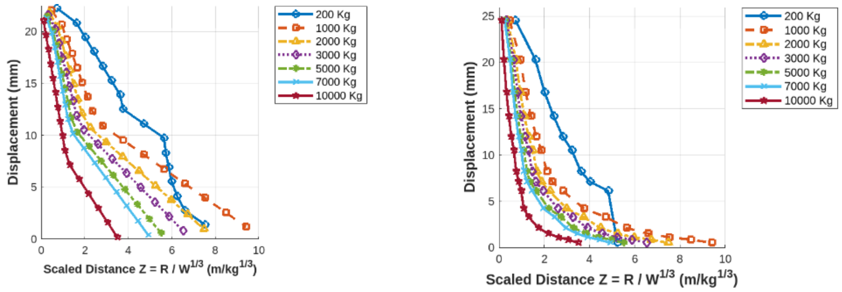

Fig. 9. Displacement vs Scaled Distance for Different Weights

The Figure 9 shows the displacement of a structure under varying blast loads with and without SSI, with different blast source weights varying between 200 Kg and 10,000 Kg. For SSI the displacement increases as the scaled distance increases, and larger weights cause greater displacement at shorter scaled distances.

For the non-SSI displacement decreases with increasing scaled distance, with larger blast weights causing more significant displacement at smaller scaled distances.

4.2 BASE SHEAR

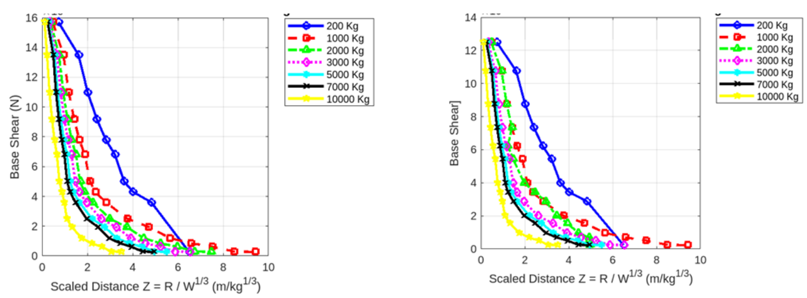

Fig. 10. Base Shear vs Scaled Distance for Different Weights

The Figure 10 plots the base shear (in N) against the scaled distance (Z = R / W^1/3) for various blast weights ranging from 200 Kg to 10,000 Kg. with and without SSI. For SSI It shows that the base shear increases with decreasing scaled distance, with larger blast weights causing higher base shear at smaller scaled distances. For the non-SSI, the base shear decreases with increasing scaled distance, with larger blast weights causing higher base shear at smaller scaled distances.

4.3 FRAGILITY CURVES

The fragility curves shown in Figure 11 illustrate the relationship between the TNT mass and the structural damage for varying levels of explosive load. In this analysis, TNT masses are considered with different mean values, specifically 200 kg, 1000 kg, 2000 kg, 3000 kg, 5000 kg, 7000 kg, and 10000 kg. A Lognormal distribution was applied to account for the uncertainty in the TNT mass. The stand-off distance, which represents the distance between the structure and the explosion, was varied in a deterministic manner to simulate different scaled distance values. This approach helps in assessing how the structural response changes under varying explosive loads and stand-off distances, providing valuable insights into the fragility of the structure

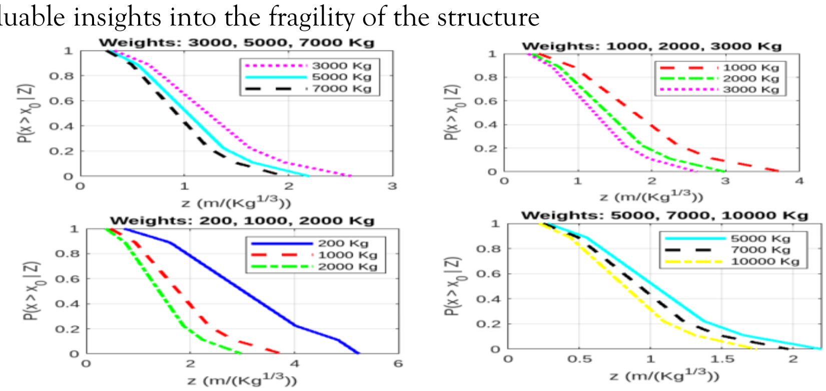

Fig. 11. Probability of Exceedance of Pressure vs. Scaled Distance for Various Blast Weights

This figure 11 illustrates how the probability of exceeding a certain pressure change with the scaled distance for different explosive weights. Each plot represents a set of explosive charges, ranging from 200 Kg to 10,000 Kg. The probability decreases as the scaled distance increases, showing that the blast's impact diminishes with distance from the explosion source. Heavier explosives produce a higher probability of exceeding the pressure threshold at shorter distances, indicating a stronger blast effect near the source and a reduced influence as the distance increases.

5 CONCLUSIONS

This study investigates the fragility of reinforced concrete (RC) structures subjected to blast loading by comparing models that consider and ignore soil-structure interaction (SSI) using SAP2000NL. A three-dimensional finite element model of a reinforced concrete building is developed. incorporating realistic material properties and SSI using Winkler foundation models. Blast loads ranging from 200 kg to 10,000 kg are applied, and dynamic analysis is performed to assess the structural reaction. Modal analysis is conducted to assess the behavior under different vibration modes. Fragility curves are created to evaluate the likelihood of failure at different blast intensities. The results demonstrate that Ignoring SSI may result in underestimating the structural vulnerability, as SSI substantially alters the displacement and base shear responses, especially under larger blast loads. The research emphasizes the significance of taking SSI into account for accurate blast-resistant design strategies and enhanced safety in blast-prone areas. It can be concluded that for high-rise buildings SSI needs to consider dynamic loads for Blast Load and earthquake.

FINDINGS:

The without SSI model shows much higher participation in UX and UY with values over 90% (94.1094% for UX and 97.8721% for UY), while the SSI model shows lower participation in these modes (around 30% to 31%).
However, in the UZ (vertical direction), the with SSI model shows significant participation (50.7459%), indicating the impact of the soil interaction on vertical motion, whereas the without SSI model shows 0.0%, indicating no contribution from this direction in the absence of SSI.
Mass Participation Factor (MPF) is more evenly distributed with SSI, indicating a more flexible structure under dynamic loading, while the model without SSI tends to overestimate the stiffness, resulting in fewer modes participating in the dynamic response
The presence of SSI alters the distribution of dynamic load participation, particularly increasing the contribution from vertical modes, which is critical in accurately assessing the structural response under blast loading.
Neglecting SSI could lead to inaccurate predictions of the structure's vulnerability to blast forces, as it would not account for the effects of foundation flexibility that affect the overall dynamic response.
MMF is observed more in SSI structure with 90 to 95% difference
Following are the modal analysis results.
The without SSI model shows a more rigid structure with very high mass participation in horizontal modes (UX and UY), but no participation in vertical acceleration (UZ).
The SSI model shows significant participation in the vertical direction (UZ), which highlights the important role of soil-structure interaction in influencing the vertical motion of the building.
In terms of mass participation in horizontal directions (UX, UY), the without SSI model contributes more, indicating the importance of including SSI for a more precise representation of the building's dynamic behavior, especially for vertical responses.
In summary, the SSI model accounts for more realistic interactions with the soil, particularly in vertical modes, while the non-SSI model overestimates horizontal participation.

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