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POST-DISASTER ASSESSMENT OF GEOTECHNICAL FAILURES IN BIHAR: LESSONS FROM FLOODS, EARTHQUAKES AND INFRASTRUCTURE FAILURES

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ABSTRACT

Bihar's complex geotechnical landscape, underlain by alluvial plains, fragile embankments, and active seismicity, has repeatedly succumbed to mega-disasters that underscore persistent deficiencies in disaster preparedness and infrastructure resilience. This paper presents three prominent case studies- the 2008 Kosi Flood, triggered by a catastrophic embankment breach; the seismic events of the 1934 and 1988 earthquakes; and a spate of recent bridge collapses, exemplified by the alarming instance of 15 bridges failing within just two months. The 2008 Kosi Flood is scrutinized with reference to maps delineating the Kosi river course, embankment layouts, and soil profiles highlighting loose silt and expansive clays. The embankment breach is attributed to overtopping, inadequate maintenance, and fundamentally unstable foundation soils. Consequential inundation displaced over two million people across multiple districts, destroyed homes, agricultural lands, and hindered access to essential services. Earthquakes of 1934 and 1988 are examined through tectonic maps, soil liquefaction zones, and ground-shaking intensity distributions. Amplification of seismic waves through soft alluvial soils intensified structural damage, causing widespread building collapse, loss of life, and long-term infrastructural disruption. Sensitivity and historical consistency analyses confirm that the DSVS framework given in the study is robust and capable of capturing district-level spatial patterns of seismic vulnerability. This paper identifies underlying factors across these disasters: heterogeneous and weak soil strata, dynamic river morphology and systemic maintenance lapses. It further highlights future high-risk zones in Bihar, such as the lower Kosi, Gandak, and Bagmati basins, where similar soil types, river behaviour and infrastructure exposure suggest potential for recurrence. The research concludes by advocating for reinforced geotechnical monitoring, embankment rehabilitation, seismic resistant design standards, real time riverbed and scour surveillance, and prioritized investments in vulnerable corridors. These measures are posited as critical components of an integrated, future ready post disaster management framework for Bihar.

KEYWORDS: Kosi Flood, Seismic Events, Bridge Collapses, High Risk Zones, Post Disaster Management

INTRODUCTION

Bihar presents a distinctly vulnerable geotechnical and hydrological setting, shaped by its location within the Indo-Gangetic alluvial plains, high groundwater conditions, dynamic river systems, and proximity to the seismically active Himalayan foreland. Thick sequences of unconsolidated sediments, combined with active tectonics and intense monsoonal hydrology, have repeatedly exposed the state's infrastructure and population to large-scale disasters, complicating long-term resilience planning. The alluvial character of the terrain is central to this vulnerability. Himalayan-fed rivers such as the Kosi, Gandak, and Bagmati transport and deposit enormous sediment loads across the floodplains of northern Bihar, creating unstable fans and highly mobile river courses. These deposits, dominated by loose sand, silt, and expansive clay, provide weak foundation conditions for embankments, bridges, and buildings. The 2008 breach of the eastern Kosi embankment near Kusaha in Nepal illustrates this condition: although river discharge was below design capacity, the embankment failed due to channel migration, heavy siltation, and poor foundation soils, compounded by inadequate maintenance and design assumptions (Sinha 2009). Authors in (Kumar and Jha 2023) present an empirical approach to flood risk mapping in the Kosi River Basin by integrating the Analytical Hierarchy Process (AHP) with Geographic Information System (GIS) techniquesThe resulting avulsion inundated large parts of Supaul, Madhepura, Purnia, and adjoining districts, causing widespread agricultural, infrastructural, and livelihood losses. Authors in (Gade 2026) identifies weak preparedness, limited early-warning reach, poor inter-agency coordination, and inadequate resilient infrastructure, and it recommends adaptive governance, stronger forecasting, reinforced embankments, financial safety nets, and climate-resilient livelihoods. Not only Bihar, in fact other states have also been witness to geotechnical failures due to natural hazards. Authors in (Kumar et al. 2025) have analyzed an RC riverine bridge in Gujarat, India, to assess how changing climate-related hazards affect bridge integrity and resilience. Authors in (Fan et al. 2025) studied combined

field investigation, in-situ and laboratory testing, monitoring, and numerical simulation to explain how extreme rainfall drives shallow loess embankment failures and to test a steel grouting pipe reinforcement method.

Bihar is also located in one of India's highest seismic risk zones. Large portions of northern Bihar fall in Seismic Zone V, and historical earthquakes have caused severe damage through ground shaking and soil liquefaction. The 1934 Nepal–Bihar earthquake resulted in extensive building collapse and surface deformation across North Bihar (Bilham 2009, Bilham et al. 2001, Fan et al. 2025, Thakur and Roy 2024b). Similarly, the 1988 border earthquake produced significant damage in districts such as Darbhanga, Madhubani, and Saharsa, where soft alluvial soils amplified seismic waves (Sitharam and Kolathayar 2013). The study by authors in (Kumar et al. 2025) presents a comprehensive flood risk assessment integrating the Analytical Hierarchy Process (AHP) with Synthetic Aperture Radar (SAR) data. Thick sedimentary layers in the Gangetic plains often intensify ground motion beyond that suggested by magnitude and distance alone, placing infrastructure designed under simplified assumptions at heightened risk (CGWB 2013 , GSI 2012). Author in (Biswas and Nath 2026) used geotechnical and geophysical data from 6000 locations and evaluated liquefaction across eight historical earthquake scenarios plus a probabilistic seismic hazard case in West Bengal. Further authors in (Thakur and Roy 2022, Thakur and Roy 2024a, Thakur and Roy 2026) uses the standard penetration borehole data of soil of Bihar for finding the liquefaction susceptibility analysis.

This study synthesizes two major case domains: the 2008 Kosi flood and the historic 2015 earthquake. Through integrated analysis of soil profiles, river morphology, embankment layouts, and seismic amplification zones, it identifies spatially concentrated future risk hotspots, particularly within the lower Kosi, Gandak, and Bagmati basins. The findings underscore the need for an integrated, multi-hazard, and future-oriented disaster management framework for Bihar that prioritizes continuous geotechnical and riverbed monitoring, embankment rehabilitation, enforcement of seismic-resistant design, real-time scour surveillance, and targeted investment in vulnerable infrastructure corridors. Bridging the gap between geological understanding, engineering practice, and institutional maintenance is essential to reducing Bihar's recurring and escalating disaster burden.

Study Area

2.1 Physiographic Division Of Bihar State

Bihar's physiography can be broadly classified into three distinct regions, the Shivalik Region, the Bihar Plain, and the Southern Plateau Region (Fig. 1) each exhibiting unique geomorphological and geological characteristics that significantly influence the state's geotechnical behavior. The Shivalik Region, located in the northern part of West Champaran district, forms the sub-Himalayan foothills and represents the youngest physiographic division of the state. Extending approximately 32 km in length and 6–8 km in width, this narrow belt of rugged terrain, composed largely of unconsolidated sediments and coarse alluvium, is prone to erosion, landslides, and slope instability. Southward of this zone lies the expansive Bihar Plain, which constitutes the largest and most dominant physiographic unit. The Ganges River traverses the plain from west to east, dividing it into two unequal segment North Bihar and South Bihar. The northern section is characterized by its flat, low-lying topography and frequent flooding caused by Himalayan-fed rivers such as the Kosi, Gandak, and Bagmati(Jain and Sinha 2004). In contrast, South Bihar comprises the fertile Gangetic plain and transitions gradually into more undulating terrain toward the plateau margins. The southernmost division, known as the Southern Plateau Region, extends from Kaimur in the west to Banka in the east and represents the ancient crystalline basement of the Indian Peninsular Block. This dissected plateau region, roughly triangular in shape, features an uneven landscape with prominent hills and valleys, including the Gaya, Rajgir, and Kharagpur hill ranges. Collectively, these three physiographic zones shape Bihar's complex geotechnical environment, influencing soil composition, groundwater dynamics, and the vulnerability of infrastructure to disasters such as floods and earthquakes.

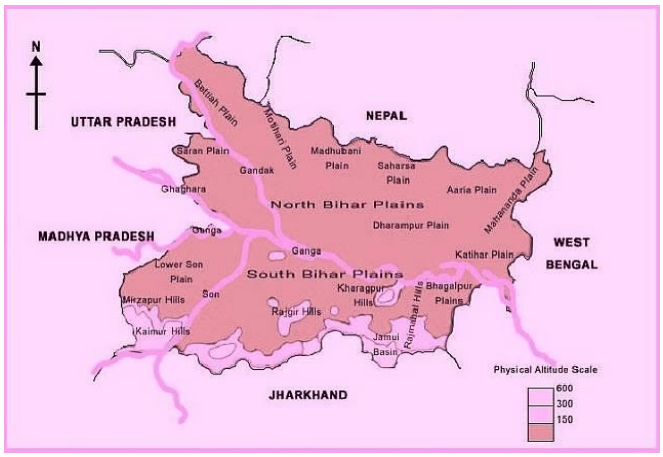


Fig. 1: Physiography of Bihar (BSDMA 2016)

2.2 River System Of Bihar

Bihar's river system is predominantly shaped by the Ganga and its Himalayan tributaries, which together define the state's hydrological and geomorphological character. The Ganga River, entering Bihar at Chausa after originating from the Gangotri Glacier in Uttarakhand, flows west to east for approximately 445 kilometres, bisecting the state into two unequal parts before exiting at Manihari. Serving as the lifeline of Bihar, it sustains agriculture, provides drinking water, and

supports dense urban settlements such as Patna, besides holding immense cultural and religious significance. Among its northern tributaries, the Kosi, Gandak, and Bagmati are particularly prominent, each contributing uniquely to the state's fluvial dynamics. The Kosi River, arising from the Saptakoshi region of Nepal (Fig. 2), is infamous for its erratic behavior and recurrent floods, earning it the title "Sorrow of Bihar". Despite its destructive tendencies, the river also enriches the plains with nutrient-rich alluvium, enhancing soil fertility. The Gandak River, originating in the Himalayas of Nepal, flows southward, forming part of the interstate boundary between Bihar and Uttar Pradesh before merging with the Ganga at Hajipur. It serves as a vital water source for irrigation and contributes significantly to the agrarian economy of northern Bihar. The Bagmati River, rising from the Mahabharata range of Nepal, enters Bihar at Sitamarhi and traverses through Darbhanga and Muzaffarpur districts, eventually joining the Ganga near Badlaghat. Revered for its religious and cultural importance, the Bagmati holds both spiritual and ecological significance for the region. Collectively, these rivers form an extensive alluvial and flood-prone drainage network, which shapes Bihar's landscape, influences its geotechnical conditions, and plays a central role in both agricultural productivity and disaster vulnerability.

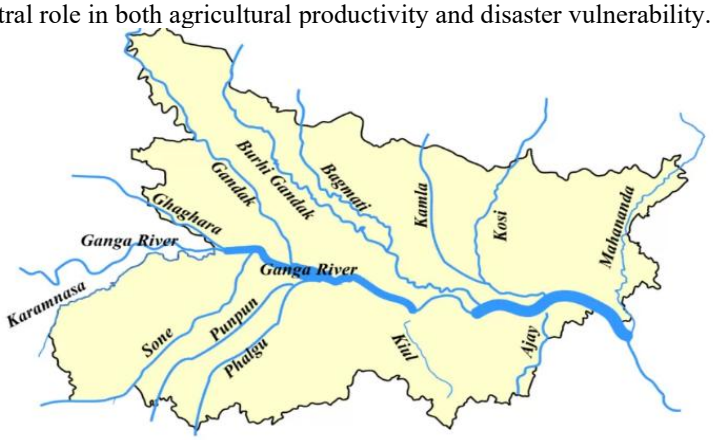


Fig. 2: River System of Bihar (Economic_Survey_of_Bihar 2019-20)

Typical Soil Types And Geotechnical Properties

Bihar's soils are broadly classified into alluvial soils of the northern and central plains and residual or lateritic soils of the southern plateau region. The Gangetic alluvial plains are dominated by sandy -silty deposits with low shear strength, high compressibility, and high permeability, making them highly susceptible to settlement, erosion, and foundation instability. In contrast, the southern regions exhibit stronger, better-drained residual soils, although their moisture sensitivity can influence slope and excavation stability. The floodplain soils of North Bihar typically possess low bearing capacity, creating persistent challenges for embankments and infrastructure development. The combination of soft, saturated alluvium and high groundwater tables significantly increases the likelihood of geotechnical failures during flood and seismic events (Table 1).

Table 1: Dominant soil types and their geotechnical properties (Prasad and Singh 2000)

District	Dominant soil types	Geotechnical Properties
Patna	Gangetic alluvium, calcareous silty clays & silty sands	Alternating sand - silt layers near Ganga, variable bearing with potential for differential settlement; require SPT/CPT for foundation depth.
Bhojpur	Riverine alluvium (silty clay, silty sand)	Generally compressible clays in floodplain; shallow spread footings possible on denser sand lenses, else ground improvement.
Buxar	Alluvium with calcareous horizons, local sandy pockets	Moderate bearing where older alluvium occurs; scour risk near riverbanks, consider pile foundations at floodplain sites.
Kaimur	Residual soils, red/brown loamy soils, patches of alluvium	Upland residual soils with better stiffness and bearing, shallower foundations feasible; local colluvium needs vetting.
Rohtas	Older alluvium, colluvial remnants, rock outcrops in parts	Mixed support, competent residual/rock zones favourable; alluvial pockets may be compressible.
Nalanda	Gangetic alluvium, silty clay & sandy interbeds	Variable bearing; compressible clays in depressions: check for high moisture/settlement susceptibility.

Saran (Chhapra)	Alluvial silts and silty sands	Loose recent alluvium in many tracts, moderate to low bearing without compaction; consider densification for foundations.
Siwan	Floodplain alluvium, silty clay, silty sand	Soft saturated clays in low areas; contamination/uranium reports in groundwater, geotech design must consider groundwater control.
Gopalganj	Gangetic alluvium, silty clay & sand lenses	Soft clays in depressions; sand lenses give variable SPT, recommend site borings.
East Champaran (Motihari)	Terai/alluvium, silty sands, peat pockets in lowlands	Terai peat/tal zones with high compressibility; piles/ground improvement where organic layers present.
Muzaffarpur	Alluvium (silt/silty sand), tal pockets	Soft silty clays and tal depressions, high settlement risk; avoid shallow foundations on peat.
Sheohar	Recent alluvium, silty sands and silty clays	Loose floodplain sands; potential liquefaction in saturated loose sands near rivers: evaluate for seismic design.
Sitamarhi	Alluvium, tal/peat in low-lying tracts	Organic and compressible tal soils locally, deep foundations often necessary.
Vaishali	Alluvium, silty clays and silty sand	Floodplain clays with moderate to high compressibility in lowlands; densified sands suitable for shallow footings.
West Champaran	Piedmont swamp, terai, alluvium	Piedmont swamp & terai, very soft/organic pockets; careful subsurface investigation required.
Araria	Recent alluvium, silty deposits	Very fine silts with high moisture in lowlands, prone to piping and high settlement.
Arwal	Alluvium, silty clay, clayey sand	Compressible alluvial clays in depressions; perform borings to determine footing depth.
Aurangabad	Mixed alluvium with local residual soils	Moderate bearing in upland patches; low-lying alluvial tracts may require improvement.
Banka	Alluvium and older alluvium near Ghats	Fine silts and clays near rivers, susceptible to scour; check for medium dense sand layers.
Begusarai	Gangetic alluvium, riverine silts	Alternating sand/silt, variable bearing and stiffness; shallow foundations possible on dense sand zones.
Bhagalpur	Floodplain alluvium; local older alluvium	Silty/clayey floodplain, soft zones near riverbanks; erosion/scour vulnerability.
Darbhanga	Alluvial silts and clays; tal areas	High silt content, localized organic layers, settlement-prone in low-lying areas.
Madhubani	Alluvium (fine silts), tal tracts	Fine silty soils; tal pockets with poor strength, ground improvement often needed.
Samastipur	Alluvial silt and silty clay	Soft lowland clays; alternative sand layers possible; site testing required.
Madhepura	Floodplain alluvium, silt/sand mixes	Fine silts and silty sands; susceptible to cyclic flooding, consider scour design.
Saharsa	Alluvium with tal/organic pockets	Extensive tal/organic soils, very low bearing and high compressibility; deep foundations common.
Supaul	Recent alluvium, silty sand, silt	Very fine floodplain deposits with compressible clays; caution for shallow footings.
Gaya	Residual soils, colluvial over Vindhyan rock, pocket alluvium	Upland residual soils and rock afford good bearing; valley alluvium may be compressible.

Jehanabad	Alluvial silts & clays	Generally compressible alluvial clays in floodplain; investigate for groundwater table effects.
Nawada	Mixed alluvium & residual soils in uplands	Better bearing on residual upland soils; alluvial lowlands need improvement.
Jamui	Older alluvium, residual soils, minor rock outcrops	Heterogeneous, residual/rock zones favorable; alluvial valleys require cautious design.
Khagaria	Riverine alluvium, silty deposits	Very fine alluvium with soft layers, high settlement and scour susceptibility.
Lakhisarai	Alluvium with older alluvial pockets	Medium compressibility clays; shallow foundations workable in denser strata.
Sheikhpura	Alluvial & residual pockets	Mixed; upland residual pockets better for foundations than low alluvial tracts.
Patna	Gangetic alluvium, calcareous silty clays & silty sands	Alternating sand - silt layers near Ganga, variable bearing with potential for differential settlement; require SPT/CPT for foundation depth.
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3. METHODOLOGY

The methodological framework for this study adopts a systematic, multi-source approach to assess geotechnical failures that have occurred in Bihar following major disaster events. The analysis integrates both primary and secondary data sources to ensure a comprehensive evaluation of the physical, structural, and socio-environmental dimensions of post-disaster geotechnical behaviour. Primary data were obtained through field surveys, soil sampling, in-situ testing, and structured interviews with local engineers, disaster management officials, and affected communities to capture ground realities and performance of geotechnical structures post-failure. Complementing this, secondary data were gathered from a range of institutional and scientific sources, including reports from the Bihar State Disaster Management Authority (2016) (BSDMA 2016), Central Water Commission (2010) (CWC 2010) and India Meteorological Department (2018) (IMD 2018) as well as satellite imagery, remote sensing datasets, and published case studies of significant events such as the 2008 Kosi embankment breach. This mixed-method approach facilitates the triangulation of data, allowing for the validation of field observations and the identification of spatial and temporal patterns in geotechnical failures. The systematic integration of these datasets supports a detailed understanding of the mechanisms, causes, and implications of

disaster-induced geotechnical instability across Bihar's diverse physiographic and soil regions. The distribution of water logged area associated with different basins of river system in Bihar has been classified in a report by Economic survey of Bihar, 2019-2020 (Economic_Survey_of_Bihar 2019-20) (Table 2).

3.1 Flood Vulnerability Of Bihar

Bihar is abundantly endowed with diverse water resources, comprising glacial-fed rivers, rain-fed rivulets, wetlands, and extensive groundwater reserves. The northern part of the state functions as a receptacle for Himalayan rivers, while the southern region is drained by rivers originating from the peninsular uplands, effectively dividing Bihar into seven distinct river basins. The major northern rivers include the Ghaghra, Gandak, Burhi Gandak, Bagmati, Kamla, Adhwara group, Kosi, and Mahananda originate in the Himalayan and glacial zones of Nepal and Tibet, and consequently, they carry enormous discharges during the monsoon season (Table 2, Fig. 3). Their flow during peak rainfall often rises 50 to 90 times above normal, leading to recurrent and large-scale flooding across North Bihar, where approximately 73.63% of the geographical area is classified as flood-prone.

Table 2: Distribution of water-logged area in different river basins (Chowdary et al. 2008)

S.No	Name of Basin and Adjoining area	Total Water-logged area in LHA
1.	Ganga	1.98
2.	Kosi	1.82
3.	Burhi Gandak	2.08
4.	Gandak	1.19
5.	Ghaghra	1.25
6.	Kiul Harohar	1.06
7.	Mahananda	0.03
Total		9.41

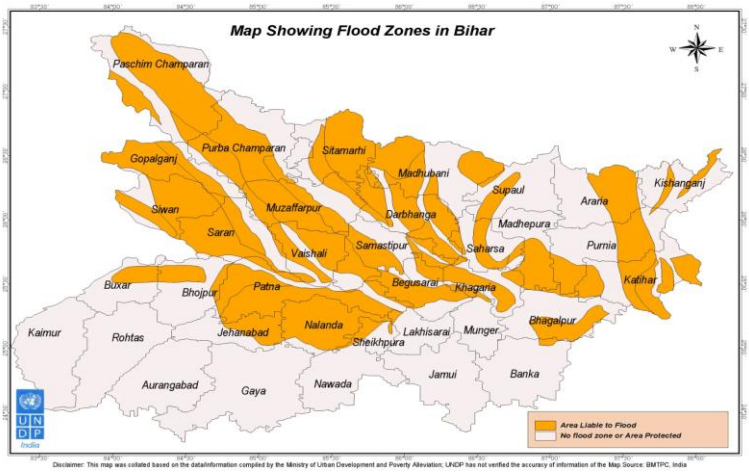


Fig. 3: Flood zones in Bihar (Udas et al. 2018)

3.3 SEISMIC ACTIVITIES IN BIHAR

Bihar lies within one of India's most seismically active regions, positioned along the boundary between the Indian and Himalayan tectonic plates near the Bihar–Nepal border. The state is intersected by six major subsurface fault lines that extend across its Gangetic plains in multiple directions, making it highly susceptible to high-intensity seismic events. According to seismic zonation data, approximately 15.2% of Bihar's total area falls within Zone V, the highest risk category. Within this zone, Madhubani and Supaul districts are entirely covered, while Araria and Sitamarhi have over 85% of their areas classified as Zone V. Districts such as Darbhanga, Madhepura, and Saharsa have between 45% and 50% exposure, with Kishanganj, Muzaffarpur, Purnia, and Sheohar showing less than 10%. A further 63.7% of the state's area lies within Zone IV, where several districts are either fully or predominantly categorized under this seismic risk level, while the remaining 21.1% falls in Zone III, indicating moderate seismic vulnerability (Fig. 4).

Historically, Bihar has experienced ten significant earthquakes over the past two and a half centuries, with magnitudes ranging between 5.5 and 8.3 on the Richter scale. Among these, the 1934 Bihar–Nepal earthquake was the most catastrophic, recording an estimated magnitude of 8.3 and causing extensive devastation across North and Central Bihar. Cities such as Munger, Patna, Muzaffarpur, and Darbhanga, along with numerous villages, suffered severe structural damage due to ground fissures, subsidence, and liquefaction, resulting in over 25,000 fatalities. The event disrupted railway lines, bridges, and communication networks across an area of nearly 36,000 km², highlighting the region's acute vulnerability to seismic-induced geotechnical failures. The most recent major seismic event, on 18 September 2011, with a magnitude of 6.8 and an epicenter in the Sikkim–Nepal region, caused moderate shaking in northern Bihar, underscoring the state's continuing exposure to active tectonic stress.

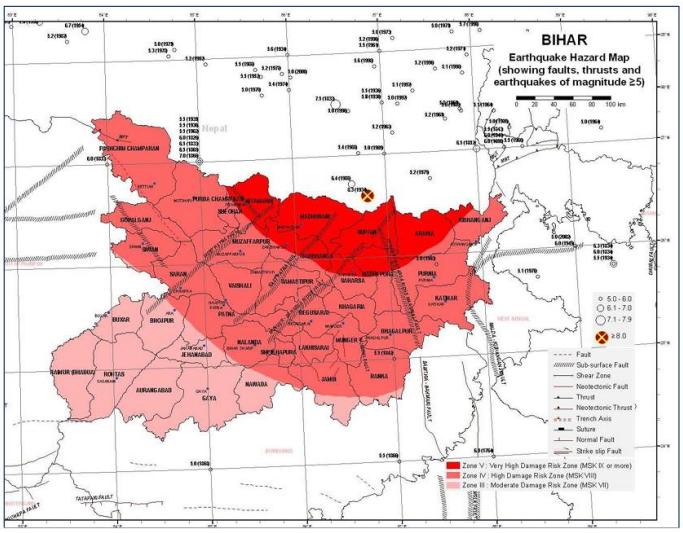


Fig. 4: Seismic zones in Bihar (BSDMA 2016)

4. Case Studies Of Geotechnical Failures

The 2008 Kosi Embankment Breach

The Kosi River is a major tributary of the Ganga, originating in the Nepal Himalaya and flowing for about 720 km before joining the Ganga at Kursela in Bihar's Katihar district. Seven tributaries merge near Triveni in Nepal, about 10 km upstream of Chatra, with the Arun, Sun and Tamur rivers forming the principal components; downstream of this confluence it is known as the Kosi River (Fig. 5).



Fig. 5: Joining of Sun Kosi, Arun & Tamur to become Kosi river (BSDMA 2016)

4.1.1. Kusaha Disaster

The Kusaha (Kosi) disaster of 2008 resulted from a breach of the Eastern Afflux Bund of the Kosi River near Kusaha village in Nepal, about 13 km upstream of the Kosi Barrage. Although the river discharge at the time (164,000 cusecs) was well below the design capacity, the failure was primarily caused by progressive channel shifting due to uneven siltation, formation of sand shoals, and inadequate maintenance of embankments. The breach triggered a major avulsion, diverting nearly 80% of the flow into abandoned palaeo channels, abruptly inundating large parts of north Bihar and affecting several districts (Fig. 6).

This event, regarded as one of the most severe flood disasters in India in the past five decades and declared a national calamity, caused extensive damage. Post-Disaster Needs Assessment reports by the World Bank, GFDRR, and the Government of Bihar documented destruction of over 330,000 houses, damage to about 1,800 km of roads and 1,100 bridges and culverts, and loss of nearly 600,000 acres of crops, severely impacting hundreds of thousands of farming households.



Fig. 6: Visual of 2008 Kosi River Flooding in Bihar (BSDMA 2016)

4.1.2 Bihar Kosi Flood Recovery Project (Bkfrp) And The Bihar Kosi Basin Development Project (Bkbdp)

Bihar Kosi Flood Recovery Project (BKFRP) and the Bihar Kosi Basin Development Project (BKBDP) were initiated to strengthen flood resilience and promote sustainable development in the Kosi River Basin. The overarching objective of BKBDP is to enhance flood resilience, improve agricultural productivity, and strengthen the capacity of the Government of Bihar to respond effectively to emergency and disaster situations in the targeted districts. The project is structured around five key components: (i) improvement of flood risk management systems, (ii) enhancement of agricultural productivity and competitiveness, (iii) augmentation of road and transport connectivity, (iv) establishment of contingent emergency response mechanisms, and (v) provision of implementation support. The BKFRP, launched in the first phase with World Bank assistance, focused primarily on immediate post-disaster recovery, including reconstruction of damaged housing, restoration of road infrastructure, and revival of livelihoods following the 2008 Kosi floods.

In its second phase, the BKBDP was designed as a longer-term basin-level intervention, addressing systemic weaknesses in flood risk management, disaster preparedness, and sustainable agricultural and infrastructure development. A major component, implemented by the Water Resources Department (WRD), aims to strengthen flood forecasting, erosion control, and sediment management through a combination of structural and non-structural measures, thereby improving Bihar's overall preparedness for future flood events.

4.1.3 Post-Disaster Needs Assessment (Pdna) For Flood Vulnerability In Bihar

Bihar is among the most flood-prone states in India, with nearly 56% of its total geographical area and over 70% of North Bihar regularly exposed to flooding. The state's hydrological system is dominated by sediment-laden Himalayan rivers such as the Kosi, Gandak, Bagmati, and Burhi Gandak, which interact with fragile embankments and unconsolidated alluvial soils to create persistent hydro-geotechnical vulnerability. On average, 28 districts experience flood impacts annually, resulting in substantial losses of life, livelihoods, crops, and critical infrastructure. Northern districts, including Sitamarhi, Supaul, Saharsa, Darbhanga, and Khagaria, experience the most severe and recurrent damage. Prolonged inundation causes soil erosion, siltation, and loss of soil fertility, directly affecting agricultural productivity and rural livelihoods. Flood-induced displacement, disruption of education and healthcare services, and increased disease burden further deepen socio-economic vulnerability and drive climate-related migration.

Geotechnically, the floodplains of Bihar are characterized by saturated, fine-grained alluvial soils with low shear strength and poor drainage capacity. These conditions contribute to embankment instability, piping, seepage, and foundation failures, exposing critical weaknesses in the design and maintenance of flood protection infrastructure. Seasonal river dynamics intensify these risks, with early monsoon flooding in northern tributaries followed by Ganga backwater effects that create extensive waterlogging and tal formation in South Bihar. The persistence and scale of flooding reflect both natural and anthropogenic drivers, including floodplain encroachment, deforestation, and population pressures. Addressing these risks requires an integrated approach that combines structural strengthening with non-structural risk reduction measures. The Post-Disaster Needs Assessment (PDNA) underscores the need for science-based planning, climate-responsive infrastructure, improved early warning systems, and stronger institutional capacity to build long-term resilience and reduce disaster risk in Bihar's flood-affected communities.

The 2015 Nepal Earthquake Effects On North Bihar

The Himalayan arc is defined by three major tectonic discontinuities, the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT) which demarcate zones of varying deformation intensity. The 2015 rupture primarily occurred on or near the MFT, but stress release along this boundary is routinely transmitted southward into the Ganga alluvial plains, including northern Bihar (Fig. 7).

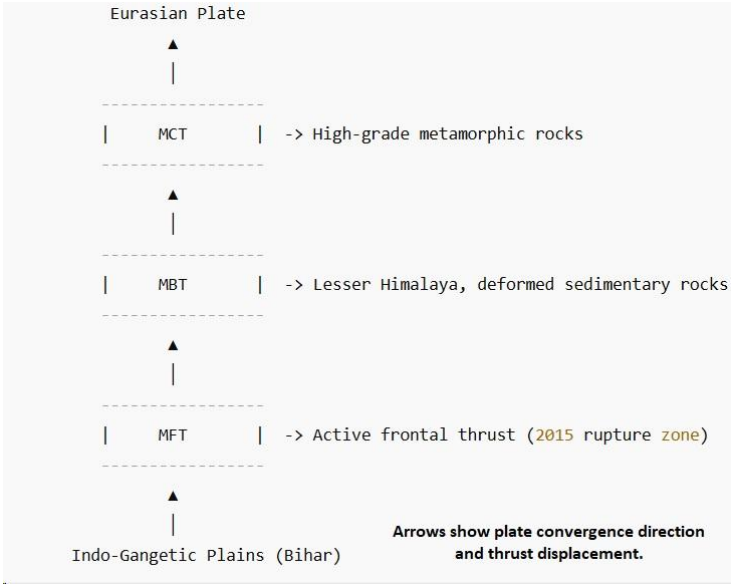


Fig. 7: Diagrammatic Representation of Himalayan Thrust System

4.2.1 Seismic Effects In Bihar

Although Bihar experienced shaking of Modified Mercalli Intensity (MMI) less than VI, the event revealed significant vulnerabilities in its predominantly non-engineered building stock. Rural districts located closest to the Nepal border, especially Sitamarhi, Madhubani, and parts of East & West Champaran, recorded prominent structural damage.

The 2015 Nepal earthquake highlighted the vulnerability of Bihar's predominantly non-engineered building stock, particularly in the northern districts located closest to the Nepal border. A large proportion of kaccha dwellings, typically constructed using stone or brick masonry bonded with mud mortar exhibited moderate to severe cracking due to their inherently low tensile and shear strength. Sitamarhi district recorded the highest damage within the state, including the complete collapse of three houses and partial collapse of 142 structures. Free-standing masonry boundary walls, parapets, and other unbraced non-structural elements suffered widespread failure, primarily attributable to inadequate out-of-plane resistance and lack of lateral confinement, demonstrating the fragility of traditional rural construction practices under even moderate seismic excitation (Table 3).

In contrast, although Reinforced Concrete (RC) frame buildings experienced comparatively limited visible damage during the event, their performance raised significant concerns from a structural safety perspective. Field observations indicate that a majority of RC structures in Bihar do not comply with the seismic provisions of IS 1893 (Indian_Standard IS_1893_(Part 1)_2002). Common deficiencies include inadequate reinforcement detailing, absence of ductile design features, soft-storey configurations, weak column, strong beam layouts, and poor-quality workmanship. While the earthquake did not induce ground motions strong enough to cause widespread RC failure, these deficiencies collectively suggest a high susceptibility to collapse under stronger shaking scenarios, underscoring the need for systematic enforcement of seismic design codes and retrofitting of existing vulnerable structures.

Table 3: District-Wise Damage Assessment In Bihar During The 2015 Nepal Earthquake (Report: Bsdma, 2016)

District	Proximity to Nepal Border	Intensity (MMI)	Types of Buildings Affected	Recorded Structural Damage	Qualitative Severity	Key Observations
Sitamarhi	Border district (~0–20 km)	V–VI	Kaccha (mud mortar), unreinforced brick masonry; some old public buildings	3 houses collapsed, 142 partially collapsed; widespread wall cracking; boundary wall failures	High	Highest damage in Bihar; weak mud-mortar dwellings most affected; non-engineered structures performed poorly.
Madhubani	Border district	V–VI	Traditional brick masonry, mud-mortar houses	Cracks in load-bearing walls, gable failures, minor roof dislodging	Moderate	Damage higher in villages near Jainagar and Laukaha; structures with older brickwork

						suffered diagonal shear cracking.
East Champaran	Close to border	V	Brick masonry, mixed RC + masonry	Cracking in masonry infill, diagonal shear cracks in walls, falling plaster	Moderate	Many houses showed out-of-plane wall bulging; non-engineered houses vulnerable.
West Champaran	Close to border	V	Mud-mortar masonry; scattered RC frames	Wall separation, parapet wall failures, minor collapse of kuccha huts	Moderate	Settlements near Bettiah and Narkatiaganj saw non-structural failures.
Darbhanga	~40–80 km from border	IV–V	Brick masonry, partial RCC	Wall cracks, ceiling plaster detachment, minor column–beam joint cracking in old RC frames	Low–Moderate	High population density increases potential risk; no major collapses.
Muzaffarpur	~50–90 km from border	IV–V	Masonry and low-rise RC	Hairline cracks, falling plaster, some infill-wall cracks	Low–Moderate	Many buildings are non-code-compliant but shaking levels were insufficient to cause collapse.
Supaul	Border-adjacent	V	Brick + mud mortar	Cracking in older houses, especially near embankment areas	Moderate	Areas closer to Nepal saw stronger shaking.
Araria	~30–60 km from border	V	Kaccha and mixed masonry	Wall and foundation cracks in older houses	Moderate	Soil conditions (alluvial) may have amplified shaking.
Kishanganj	Bordering Nepal & Bengal	IV–V	Masonry	Minor cracking, no major structural failure	Low	More distant from the fault rupture directivity.
Sheohar	Very close to Sitamarhi	V	Mud-mortar masonry	Wall cracks, localized partial collapse	Moderate	Vulnerability similar to Sitamarhi but lower reported damage.
Saharsa	~80–120 km	IV	Masonry	Internal plaster cracks	Low	No structural damage reported.
Purnea	~100+ km	IV	Masonry	Minor non-structural cracks	Low	Shaking perceived strongly but harmless.
Katihar	~100+ km	IV	Masonry	Non structural damage only	Low	No building collapse.

Other Central & Southern Bihar Districts (Patna, Gaya, Nalanda, Bhojpur, Rohtas)	150–250+ km	III–IV	RC + masonry	Very light or no damage	Very Low	Only perceptible shaking; no structural concerns.
District	Proximity to Nepal Border	Intensity (MMI)	Types of Buildings Affected	Recorded Structural Damage	Qualitative Severity	Key Observations
Sitamarhi	Border district (~0–20 km)	V–VI	Kaccha (mud mortar), unreinforced brick masonry; some old public buildings	3 houses collapsed, 142 partially collapsed; widespread wall cracking; boundary wall failures	High	Highest damage in Bihar; weak mud-mortar dwellings most affected; non-engineered structures performed poorly.

4.2.2. Ascii Damage Distribution Map For Bihar (2015 Nepal Earthquake)

The ASCII damage distribution map for Bihar provides a qualitative representation of spatial variation in seismic impacts using symbolic density to indicate damage intensity. Northern border districts such as Sitamarhi, Madhubani, Supaul and East Champaran exhibit higher symbol concentration, reflecting greater damage due to proximity to the epicentral region and amplification by soft alluvial sediments. Central districts display moderate damage patterns, while southern districts show attenuated impacts consistent with southward decay of seismic energy from the Himalayan source (Fig. 8). The map highlights the influence of local site conditions and the vulnerability of unreinforced masonry structures, serving as a rapid visualization tool for preliminary seismic damage assessment in data-constrained environments.

Nepal (Epi-Centre Region)

[redacted]

Strong Shaking

(MMI VII–VIII)

▲

|

---------- Nepal Border

|

[redacted] [redacted] [redacted]

Sitamarhi Madhubani Supaul

High Damage Zone (MMI V–VI)

- Collapses & major cracking
- Kaccha failures common

[redacted] [redacted]

East Champaran West Champaran

Moderate Damage (MMI V)

- Masonry wall cracks
- Parapet/gable failures

[redacted] [redacted]

Darbhanga Muzaffarpur

Low–Moderate Damage (MMI IV–V)

- Infill cracks
- Non structural damage

[redacted] [redacted] [redacted]

Saharsa Araria Kishanganj

Low Damage (MMI IV)

- Minor plaster cracking

---------- Central Bihar

Patna Gaya Nalanda (Mmi Iii–Iv)

Very Low Damage

- Perceptible shaking only

Fig. 8: Damage Distribution Map for 2005 Bihar-Nepal earthquake

4.2.3. Vulnerability Scoring Formula

To assess district-level seismic vulnerability in Bihar, a composite index termed the District Seismic Vulnerability Score (DSVS) was developed using a multi-criteria decision analysis approach. The index integrates four key parameters representing dominant physical vulnerability drivers in the region: Building Typology Vulnerability (BTV), Code Compliance and Structural Quality (CCQ), Soil and Site Amplification Potential (SAP), and Observed/Recorded Damage Factor (ODF). Each parameter was normalized on a 0–5 ordinal scale to ensure comparability across districts with heterogeneous building stock, geological conditions, and historical seismic exposure. The final DSVS was computed using a weighted linear combination, with weights assigned based on a review of established seismic vulnerability frameworks (NDMA, 2008 guidelines) (NDMA 2008) and expert judgment regarding regional construction practices in the Indo-Gangetic Plain. Greater emphasis was placed on structural typology and construction quality, as non-engineered and poorly detailed masonry buildings are widely recognized as the principal contributors to seismic damage in India, while soil amplification and historical damage were incorporated as modifying factors. Similar composite and weighted vulnerability indices have been widely adopted in regional seismic risk assessments where detailed building-level data are unavailable. The score integrates four primary parameters that influence earthquake performance in the region: Building Typology Vulnerability (BTV), Code Compliance and Structural Quality (CCQ), Soil and Site Amplification Potential (SAP), and Observed or Recorded Damage Factor (ODF). Each parameter is assigned a value on a 0–5 scale, where 0 indicates negligible vulnerability and 5 represents highest vulnerability. This normalization allows comparison across districts with differing building stock, geological conditions, and historical seismic exposure.

The DSVS is computed using a weighted linear combination of the four parameters:

$$DSVS = 0.35(BTV) + 0.30(CCQ) + 0.20(SAP) + 0.15(ODF)$$

Where, Building Typology Vulnerability (BTV; 0–5): Represents the proportion of highly vulnerable structures such as kaccha houses, mud-mortar masonry, unreinforced brick masonry, and other non-engineered forms of construction. Code Compliance & Structural Quality (CCQ; 0–5): Evaluates adherence to seismic design provisions (IS 1893), reinforcement detailing standards, presence of soft-storey configurations, and overall construction quality. Soil & Site Amplification Potential (SAP; 0–5): Assesses local geological conditions, including soil type (soft alluvial deposits scored as 5; hard rock as 1), groundwater levels, and susceptibility to amplification or liquefaction. Observed/Recorded Damage Factor (ODF; 0–5): Based on empirical damage observed during major earthquakes affecting the region (e.g., the 2015 Nepal–Gorkha event or the 1934 Nepal–Bihar earthquake), enabling historical calibration of vulnerability.

The weighting scheme reflects the relative influence of each factor on district-level seismic vulnerability. Building Typology Vulnerability (35%) receives the highest weight due to the dominance of non-engineered rural structures in Bihar, which have historically exhibited poor seismic performance. Code Compliance and Structural Quality (30%) is the second most influential factor, acknowledging the widespread deficiencies in reinforcement detailing and design practices in RC buildings across the state. The Soil and Site Amplification Potential (20%) accounts for the soft alluvial deposits of the Ganga basin, which are known to amplify ground motion. Finally, the Observed Damage Factor (15%) ensures that the scoring system incorporates empirical evidence from past earthquakes, reinforcing the validity of the model. Validation of the DSVS was performed using sensitivity and consistency analyses. A sensitivity analysis was conducted by systematically varying individual parameter weights within ±15% of their baseline values while maintaining a unitary sum, and recalculating district-level vulnerability rankings. Results indicate that relative district rankings remain largely stable under reasonable weight perturbations, demonstrating the robustness of the proposed formulation. In addition, a historical consistency check was carried out by comparing DSVS results with documented damage patterns from major earthquakes affecting Bihar, including the 1934 Nepal–Bihar earthquake and the 2015 Nepal–Gorkha event.

7. RESULTS AND DISCUSSION

This study reveals that Bihar's disaster vulnerability is fundamentally driven by its geotechnical and geomorphological setting, compounded by structural and institutional weaknesses. The case-based analysis of the 2008 Kosi flood, historic earthquakes (1934 and 1988), the 2015 Nepal earthquake impacts, and recent bridge failures shows consistent spatial clustering of damage in the North Bihar alluvial plains, particularly within the Kosi, Gandak, Bagmati and lower Ganga sub-basins. The geotechnical assessment confirms that most flood-prone districts are underlain by soft, saturated silts and clays with low shear strength and high compressibility, leading to repeated embankment instability, piping, scour, and foundation failures. Districts such as Supaul, Saharsa, Madhepura, Khagaria, Sitamarhi and Darbhanga exhibit the poorest foundation conditions and highest incidence of recurring flood damage.

Application of the District Seismic Vulnerability Score (DSVS) model demonstrates that districts closest to the Nepal border, Sitamarhi, Madhubani, Supaul, Araria, Saharsa and Darbhanga record the highest composite seismic vulnerability, driven primarily by the dominance of non-engineered housing, poor code compliance in RC construction, and strong site amplification due to thick alluvial sediments. Fig. 10 shows major factors leading to damages during earthquake in Bihar. Central and southern districts such as Patna, Gaya, Rohtas and Aurangabad consistently show lower vulnerability owing to relatively stiffer soils and more engineered building stock. This research concludes that Bihar's recurring disaster losses are not primarily the result of extreme natural events alone, but rather of systemic geotechnical fragility combined with vulnerable construction practices and institutional gaps in design, monitoring and maintenance. The alluvial plains of

North Bihar function as a high-amplification, low-strength foundation environment where even moderate floods or earthquakes can trigger large-scale structural failures.

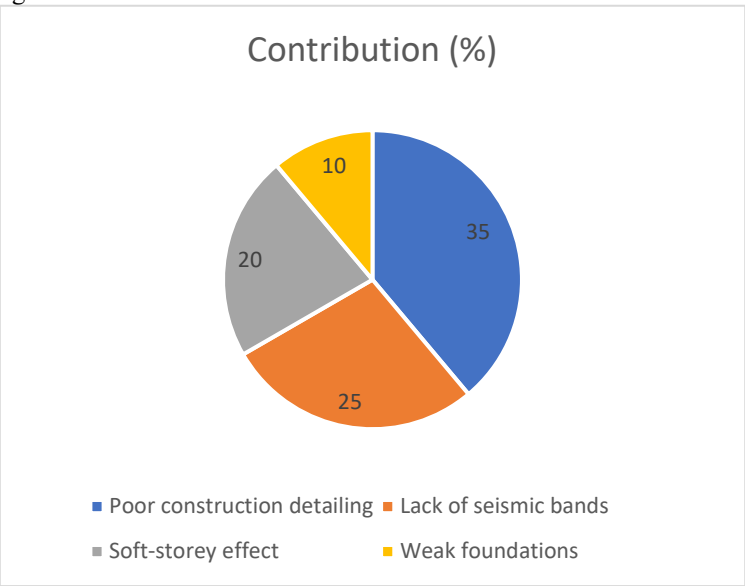


Fig. 9: Primary Causes of Earthquake Damage in Bihar (%)

The 2008 Kosi embankment breach demonstrated that embankments constructed on weak, fine-grained deposits cannot perform reliably without continuous maintenance, sediment management and real-time monitoring. Historical and recent earthquake analyses confirm that soft alluvial soils significantly amplify seismic shaking, while the predominance of non-engineered masonry and non-compliant RC frames drastically increases collapse risk under stronger future earthquakes. District-level application of the DSVS model establishes a reproducible framework for prioritising interventions, identifying Sitamarhi, Madhubani, Supaul, Saharsa, Darbhanga, Madhepura, and Khagaria as the most critical multi-hazard districts in Bihar.

Overall, the results establish a clear multi-hazard pattern in which flood, seismic and infrastructure risks overlap spatially, creating compound disaster hotspots in North Bihar. The disaster risk reduction in Bihar requires a shift from reactive, event-based responses to a proactive, geotechnically informed resilience strategy. Systematic soil and river-bed monitoring, mandatory seismic code enforcement, embankment rehabilitation, bridge-scour surveillance, and targeted retrofitting of vulnerable buildings are essential to building a future-ready disaster management framework. Without such integrated interventions, Bihar will remain exposed to recurrent, cascading infrastructure and human losses in the face of future floods and earthquakes.

8. Mitigation And Policy Recommendations

To reduce Bihar's chronic flood vulnerability, mitigation strategies must integrate geotechnically robust structural interventions with governance and community-based measures. Priority actions include rehabilitation and redesign of embankments using scientifically validated geotechnical standards, improved seepage control through filters and geosynthetics, and sediment management based on basin-wide hydrological assessments. Strengthening flood forecasting and early warning systems, coupled with real-time data sharing between agencies, is essential for timely evacuation and disaster preparedness. Land-use zoning and strict enforcement of floodplain regulations should be institutionalized to limit unplanned settlements in high-risk zones. Agricultural resilience must be enhanced through soil rehabilitation, drainage improvement, and promotion of flood-tolerant cropping systems. Institutional capacity building, regular maintenance of flood control infrastructure, and community-based disaster risk management should be mainstreamed to ensure sustainable, long-term reduction of flood risk under changing climatic and hydrological conditions.

Despite its high exposure to recurrent flooding, Bihar possesses substantial land, water, and human resource potential. Achieving convergence with national economic growth trajectories necessitates the adoption of holistic, outcome-oriented flood risk management strategies. Immediate priorities should concentrate on the Kosi basin, emphasizing (i) risk reduction through integrated structural and non-structural measures, and (ii) preparation of a state-wide flood risk management master plan. In the long term, Kosi-specific interventions should be scaled up across the entire state, supported by systematic implementation of integrated flood risk management frameworks.

8.1 Hazard-Specific Mitigation And Preparedness Strategies For Floods In Bihar

Risk reduction strategies increasingly recognize the multi-hazard nature of Bihar's disaster landscape. Earthquake risk mitigation prioritizes structural safety through seismic retrofitting of vulnerable buildings, mandatory compliance with earthquake-resistant design codes for new construction, and institutional capacity building of engineers, architects, and skilled masons. Flood risk management focuses on structural and non-structural drivers of inundation, particularly in North Bihar where large catchments, steep channel gradients, and weakened alluvial foundations intensify flood hazards (Table 4). In South Bihar, flooding is predominantly caused by restrictive embankments, adverse topographic gradients and inadequate drainage infrastructure.

A major policy gap has been the limited attention given to sedimentation and silt management, despite their critical role in altering river conveyance capacity. A comprehensive strategy must therefore integrate flood and drought management through the revival of traditional water harvesting systems (ponds, reservoirs, ahars and pynes), river interlinking, rainwater harvesting, micro-hydropower initiatives, and structured community-level disaster preparedness programmes.

Table 4. Priority Flood And Multi-Hazard Mitigation Measures In Bihar

Hazard Type	Key Structural Measures	Key Institutional / Non-Structural Measures
Floods	Embankment strengthening, geosynthetics, deep foundation works, channel training	Floodplain zoning, early warning systems, community preparedness
Earthquakes	Seismic retrofitting, code-compliant building design	Training of engineers, masons and planners
Sedimentation	Desiltation, sediment bypass and river training structures	Basin-scale sediment monitoring and management policies

8.2 Mitigation And Policy Recommendations For Seismic Risk In Bihar

To reduce Bihar's seismic risk, an integrated approach combining structural retrofitting, regulatory enforcement, and institutional capacity building is essential. Priority should be given to strengthening non-engineered masonry buildings in high-risk districts such as Sitamarhi, Madhubani, and Champaran through seismic bands, vertical reinforcement, improved mortar, and confined masonry. Strict enforcement of national seismic codes (IS 1893) must be institutionalized, with mandatory third-party review for critical infrastructure. State-level seismic safety policies should mandate structural audits and phased retrofitting of vulnerable RC buildings, including soft-storey and poorly detailed frames. Local bodies must be strengthened through trained inspectors and digital permitting systems to ensure compliance. Upgrading rural housing using cost-effective earthquake-resistant technologies, securing non-structural elements, and institutionalizing certified training for engineers and masons are critical. Community preparedness should be enhanced through awareness programmes, drills, and school-based earthquake safety education.

Finally, seismic micro-zonation should be integrated into district disaster management plans and land-use policies, ensuring that critical infrastructure is sited and designed based on site-specific hazard assessments. Strengthening real-time seismic monitoring networks and emergency response coordination will be essential for minimizing casualties and economic losses during future earthquake events (Table 5).

Table 5: Recommended Seismic Mitigation Actions

Action Area	Intervention	Expected Outcome
Building safety	Seismic retrofitting of masonry houses	Reduced collapse risk
Engineering practice	Training of masons & engineers	Improved construction quality
Regulatory framework	Strict enforcement of IS codes	Safer new constructions
Planning	Seismic micro-zonation	Risk-informed land use
Emergency response	Community drills and preparedness	Lower casualties

9. CONCLUSIONS

Bihar's disaster vulnerability is fundamentally controlled by its geotechnical and geomorphological setting, particularly the extensive alluvial plains of North Bihar characterized by soft, saturated silts and clays with low shear strength and high compressibility.

Case studies, including the 2008 Kosi embankment breach, demonstrate that catastrophic failures are often driven by sediment-induced channel instability, embankment distress, and inadequate maintenance, rather than extreme hydrological loading alone.

Flood impacts show strong spatial clustering in the Kosi, Gandak, Bagmati, and lower Ganga sub-basins, where weak foundation conditions lead to recurrent embankment failures, piping, scour, and infrastructure damage.

Analysis of the 2015 Nepal–Gorkha earthquake confirms that Bihar's seismic risk is primarily vulnerability-driven, as moderate shaking intensities (MMI IV–VI) caused disproportionate damage to non-engineered structures.

Kaccha and mud-mortar masonry buildings exhibited the poorest seismic performance due to low tensile and shear capacity, lack of confinement, and absence of seismic detailing.

Although reinforced concrete buildings showed limited visible damage, widespread non-compliance with IS 1893 and poor construction quality indicate a high collapse potential during stronger future earthquakes.

Application of the District Seismic Vulnerability Score (DSVS) identifies northern border districts of Sitamarhi, Madhubani, Supaul, Araria, Saharsa, and Darbhanga as the most seismically vulnerable, driven by fragile building typologies and strong site amplification from alluvial sediments.

Central and southern Bihar districts generally exhibit lower vulnerability due to relatively stiffer soils and a higher proportion of engineered construction.
The study concludes that Bihar's recurring disaster losses result from the interaction of natural hazards with fragile ground conditions, vulnerable construction practices, and institutional gaps in design, monitoring, and maintenance.
Effective risk reduction requires an integrated, multi-hazard approach, combining geotechnical strengthening, improved embankment management, strict enforcement of seismic design codes, retrofitting of existing structures, and basin-scale flood and sediment management.
The proposed DSVS framework offers a transparent and replicable tool for prioritizing districts for seismic risk mitigation and can support evidence-based planning and resilience-building in Bihar and similar alluvial floodplain regions.

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