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WHITHER PERFORMANCE-BASED ENGINEERING IN INDIA?

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ABSTRACT

The Kutch Earthquake of January 26, 2001 in Gujarat, India, caused the destruction of a large number of modern 4 to 10-storied buildings. After this earthquake, doubts arose about our professional practices, building by-laws, construction materials, building codes and education for civil engineers and architects. It led to large number of short-term courses and workshops, revision of the seismic code, and initiation of a National Programme on Earthquake Engineering Education (NPEEE). Based on an extensive damage survey of the region, comparisons among old and new seismic codes in India and Performance Based Engineering (PBE) based draft codes in US, documents produced under NPEEE, and the unabated popularity of seismically vulnerable constructions in India, this paper gives the prospects for PBE in India. It lists the pre-requisites that made the emergence of PBE possible in California, compares the situation in India and discusses the tasks and difficulties for implementing PBE in India.

KEYWORDS: Performance Objectives, Building Standards, Kutch Earthquake, Seismic Zones, Engineering Education

INTRODUCTION

The unexpected large-scale damage to modern structures, that complied with modern building codes, during the Northridge Earthquake of January 17, 1994, came as a rude shock, particularly because earthquakes of even greater magnitude and intensity are expected in California. Also, the lessons from seismic damage observed in past earthquakes had already been incorporated in building codes of California. Approved member connections had already been tested full-scale in laboratories. Quality control and inspection procedures were stringent and responsibilities of different stakeholders were well established. Analytical procedures and computer programs used for analyses and design were well tested and used by a large number of design firms.

Building codes, prior to the Northridge Earthquake, used force-based analytical methods for design against both gravity and lateral loads. Benefit of ductility in lateral load resisting system was taken to scale down elastic level seismic lateral loads to the level for design. Capacity design method was used to ensure robust inelastic behavior for the chosen collapse mechanism for the lateral load resisting system. The following two deficiencies were identified for the unacceptable damage that occurred in many structures during the Northridge Earthquake (MBDSI, 2000; EERI, 1995).

1. Designers often conceived independent structural systems to support gravity loads and for resisting earthquake lateral loads. The lateral load resisting system was designed for high levels of ductility. For gravity loads, the benefit of ductility cannot be taken, and, therefore, the gravity load resisting system was designed to be non-ductile. Consequently, the lateral load resisting system tended to be flexible with a high level of ductility, whereas members of the gravity load resisting system tended to be relatively stiff, low in strength and brittle for lateral loads. Problems arose because the two incompatible systems were connected by floors and underwent identical lateral deformations. These deformations were high due to the flexible and ductile nature of the lateral load resisting system. The brittle gravity load system rapidly lost its gravity load carrying capacity during these lateral deformations leading to progressive collapse of the structure. This happened in some parking structures.
2. In the seismically invulnerable moment resisting steel frame buildings, unacceptable damages occurred due to unanticipated under-strength and brittle nature of the beam-to-column welded connections compared to the beam sections. Capacity design method was used to ensure a strong column and weak beam design. Welded-connections were used between beams and columns. To

ensure that flexural plastic hinging occurs in the beam section away from the joint region, the welded-connections were designed to be stronger compared to the beams. Unfortunately, steel beams with strengths much higher than their specified nominal strengths were inadvertently used. This caused beams to be stronger than the welded-connection and the joint region became the critical region. However, the welded-connection was brittle, owing to its very small dimensions, and the expected ductilities were not manifested during the earthquake. Remedies involved techniques to shift the critical region away from the welded-connection and into the beam member.

The first deficiency showed the flaws of using the force-based methods for design. The inconsistency between prescribed linear analyses techniques (viz. response spectrum, mode superposition and linear dynamic) and specification of reduced seismic loads for design, based on ductile non-linear behaviour, led to unacceptable seismic performance. Consideration of displacement compatibility between gravity and lateral load resisting systems could have identified the problem. PBE sought to correct this by developing more precise performance criteria, more precise specification of earthquake loads and by developing guidelines and acceptance criteria for non-linear static and non-linear dynamic analyses for evaluation of existing, retrofitted and new structures (ATC, 1996; FEMA, 1997a, 1997b, 2000). Tools for non-linear static and dynamic structural analyses were readily available in the form of DRAIN family of computer programs developed by the author (Prakash and Powell, 1993). The DRAIN-2DX program was used in all the five case studies reported in ATC-40: Volume 2 (ATC, 1996) to evaluate the Capacity Spectrum method developed in ATC-40: Volume 1 (ATC, 1996) for PBE.

The second deficiency showed the importance of having stricter norms for manufacture of structural materials and for their field-testing. PBE documents emphasize these too. Such deficiencies cannot be remedied by computer analyses.

Non-linear analyses did not initially provide a method for earthquake resistant design. They only provided an evaluation procedure. PBE based non-linear analyses (ATC, 1996; FEMA, 1997a, 2000) were, therefore, first used for evaluation of existing structures that did not meet the provisions of the latest building codes. They were also handy for evaluating possible retrofit schemes. Draft codes for designing new buildings using PBE were subsequently developed (FEMA, 1997b).

In India, the Kutch Earthquake of January 26, 2001 in Gujarat too caused the destruction of a large number of modern 4-to-10 storied buildings as far as 350 km away from the epicenter (EERI, 2002). After this earthquake, doubts arose about our professional practices, building by-laws, construction materials, building codes and education for civil engineers and architects. It led to the revision of the seismic code and initiation of a National Programme on Earthquake Engineering Education (NPEEE) (MHRD, 2003).

The author conducted a composite damage survey during February 4 to 15, 2001 for the Kutch Earthquake. The survey included houses in rural and urban areas; reinforced concrete buildings of schools, hospitals, community inns and government offices; temples; 4-6 story buildings; infrastructure buildings such as overhead water tanks, substations of Gujarat Electricity Board, roads, bridges, industrial buildings and oil installations; and ground damage (Prakash et al., 2001a, 2001b, 2001c, 2001d, 2001e, 2001f; Sinvhal et al., 2001a, 2001b, 2001c, 2001d, 2001e, 2001f, 2001g, 2001h, 2001i). For each type of structure, the quality of construction and presence of critical deficiencies were investigated. Heavy damage and destruction of multistoried buildings in Ahmedabad (epicentral distance > 250 km) on Sabarmati river and in Surat (epicentral distance > 350 km) on Tapi river are attributable to the presence of weak and soft ground stories used for parking, aggravated by the ground response of underlying soft alluvium river deposits. The author is distressed to see that such construction is still popular in cities of India owing to the seriously flawed seismic standards in India. These standards actually promote seismically unsafe constructions; and, in order to deflect culpability, after damaging earthquakes, imbibe half-hearted cautions against such constructions. This feature of our seismic standards is highlighted repeatedly in this paper to motivate PBE in India.

The Ministry of Human Resources Development organized a meeting on 17th August 2001 with a view to give a special thrust to earthquake engineering education in India. The author attended this meeting as a representative of the Department of Earthquake Engineering. This meeting led to a National Programme on Earthquake Engineering Education (MHRD, 2003). The need to imbibe the needed elements of earthquake engineering in the bachelor’s curricula for civil engineers was emphasized at this meeting. Since then the author has been exploring ways to fulfill this need. During this exploration, the author came across many debilitating changes that occurred in civil engineering education during the past

50 years. Some of these changes adversely affect implementation of PBE. These are also discussed in this paper to motivate PBE in India.

SEISMIC PERFORMANCE OBJECTIVES IN INDIA

In India, the criteria for earthquake resistant design of structures are given in IS 1893, published by the Bureau of Indian Standards (BIS). Initially formulated in 1962, this standard was subsequently revised in 1966, 1970, 1975, 1984 and 2002 (BIS, 1962, 1966, 1970, 1975, 1984, 2002). In its fifth revision, IS 1893 was split into five parts, and so far only IS 1893-2002 (Part 1), covering general provisions and buildings, has been published. The other parts – dealing with (a) Liquid retaining tanks, (b) Bridges and retaining walls, (c) Industrial structures including stack like structures, and (d) dams and embankments – have remained essentially unchanged since 1962. Besides IS 1893, BIS has published the following Indian Standards for earthquake resistant design of structures (BIS, 1993a, 1993b, 1993c, 1993d, 1993e):

1. IS 4326-1993: Earthquake Resistant Design and Construction of Buildings – Code of Practice (2nd revision, first published in 1967, first revised in 1976)
2. IS 13827-1993: Improving Earthquake Resistance of Earthen Buildings – Guidelines
3. IS 13828-1993: Improving Earthquake Resistance of Low Strength Masonry Buildings – Guidelines
4. IS 13920-1993: Ductile Detailing of Reinforced Concrete Structures subjected to Seismic Forces – Code of Practice
5. IS 13935-1993: Repair and Seismic Strengthening of Buildings – Guidelines.

IS 1893-1962 and IS 1893-1966 divided the country into seven seismic zones – 0, I, II, III, IV, V and VI – based on the maximum Modified Mercalli Intensities (MMI) historically observed or expected in those zones. IS 1893-1970 reduced the number of seismic zones to five by merging zone 0 with zone I, and zone VI with zone V. It also introduced the Comprehensive Intensity Scale (CIS-64) as an alternative to the MMI scale for seismic zoning. IS 1893-2002 further reduced the number of seismic zones to four by merging zone I with zone II and adopted a modified CIS-64 scale for seismic zoning and dropped references to the MMI scale. The mapping of zones to intensities in IS 1893-2002 is given in Table 1.

Table 1: Mapping Seismic Zones to Intensities in IS 1893-2002

In IS 1893-1962 and IS 1893-1966		**In IS 1893-1970, IS 1893-1975 and IS 1893-1984**		**In IS 1893-2002**	
Seismic Zone	**Mapped to MMI Scale**	**Seismic Zone**	**Mapped to MMI Scale with CIS-64 Scale Offering an Alternative Description**	**Seismic Zone**	**Mapped to a Modified CIS-64 Scale**
0	Below V				
I	V	I	V and below		
II	VI	II	VI	II	VI and below
III	VII	III	VII	III	VII
IV	VIII	IV	VIII	IV	VIII
V	IX	V	IX and above	V	IX and above
VI	X and above				

A critical appraisal of these standards shows that BIS consistently avoids accepting the goal of ensuring life-safety as a minimum criterion for earthquake resistant design of ordinary structures, so that seismically vulnerable constructions may continue to have its sanction in highly seismic areas of the country, albeit with certain earthquake resistant features. Thus, in its Foreward, IS 1893-2002 expresses the desired performance objective as follows (with author’s emphasis): “It is not intended in this standard to lay down regulations so that no structure shall suffer any damage during earthquakes of all magnitudes.

It has been endeavoured to ensure that, as far as possible, structures are able to respond, without structural damage to shocks of moderate intensities and without total collapse to shocks of heavy intensities. While this standard is intended for earthquake resistant design of normal structures, it has to be emphasized that in the case of special structures, detailed investigations should be undertaken, unless otherwise specified in the relevant clauses."

The damage states 'structural damage' and 'total collapse' are defined in CIS-64 and do not ensure life-safety as shown subsequently. IS 1893-1984 (Clause 0.4.1) further clarifies this as follows (with author's emphasis): "… Similarly, in highly seismic areas, construction of a type which entails heavy debris and consequent loss of life and property, such as masonry, particularly mud masonry and rubble masonry, should be avoided in preference to construction of a type which is known to withstand seismic effects better, such as construction in light weight materials and well-braced timber framed constructions …"

The above clause does not prohibit seismically vulnerable constructions, it merely cautions against them. In IS 1893-2002, the above caution is further weakened by promoting the construction of seismically more vulnerable earthen buildings as per IS 13827 and low-strength masonry buildings as per IS 13828 in highly seismic areas instead of the more robust well-braced timber framed constructions, as follows (with author's emphasis): "… In highly seismic areas, construction of a type, which entails heavy debris and consequent loss of life and property, such as masonry, particularly mud masonry and rubble masonry, should preferably be avoided. For guidance on precautions to be observed in the construction of buildings, reference may be made to IS 4326, IS 13827 and IS 13828. …"

CIS-64 is introduced in Appendix D-2 in IS 1893-1970, IS 1893-1975 and IS 1893-1984 and in Annexure D in IS 1893-2002 (Part 1), as follows: "The scale was discussed generally at an inter-governmental meeting convened by UNESCO in April 1964. Though not finally approved, the scale is more comprehensive and describes the intensity of earthquake more precisely. …"

Thus, the scale clearly does not have international approval, and none was actually needed for incorporation as the intensity scale in the Indian Standard. The allusion to a meeting convened by UNESCO is intended to ensure that the scale is not looked with suspicion in India. The above introduction also implies that the CIS-64 scale should have remained unchanged in IS 1893-1970, IS 1893-1975, IS 1893-1984 and IS 1893-2002. Surprisingly, the CIS-64 scale in IS 1893-2002 (Part 1) is different from the CIS-64 scale in IS 1893-1970, IS 1893-1975 and IS 1893-1984 with regard to how damage to buildings is classified. This is shown by the changes in the definitions in CIS-64 as reproduced below:

a) Type of Structure (Buildings):

Type A	Buildings in fieldstone, rural structures, un-burnt brick houses, clay houses.
Type B	Ordinary brick buildings, buildings of the large block and prefabricated type, half-timbered structures, buildings in natural hewn stone.
Type C	Reinforced buildings, well built wooden structures.

b) Definition of Quantity:

Single, Few	About 5%
Many	About 50%
Most	About 75%

c) 'Classification of Damage to Buildings' in IS 1893-1970, IS 1893-1975 and IS 1893-1984:

Grade of Damage	**Brief Description**	**Description** (with author's emphasis)
Grade 1	Slight Damage	Fine cracks in plaster; fall of small pieces of plaster
Grade 2	Moderate damage	Small cracks in walls; fall of fairly large pieces of plaster, pantiles slip off; cracks in chimneys; parts of chimney fall down
Grade 3	Heavy damage	Large and deep cracks in walls; fall of chimneys

Grade 4	Destruction	Gaps in walls; parts of buildings may collapse; separate parts of the building lose their cohesion; and inner walls collapse
Grade 5	Total damage	Total collapse of buildings

IS 1893-2002 has the following descriptions for Grade 2 and Grade 3 damage states:

Grade 2	Moderate damage	Small cracks in plaster; fall of fairly large pieces of plaster, pantiles slip off; cracks in chimneys; parts of chimney fall down
Grade 3	Heavy damage	Large and deep cracks in plaster; fall of chimneys

Thus, the word "walls" has been surreptitiously replaced by the word "plaster" in IS 1893-2002. These changes are obviously in error. With these changes, for Grade 2 damage, we have fall of fairly large pieces of plaster arising out of only small cracks in plaster. For Grade 4 damage, we have gaps in walls, but in Grade 3 damage, we don't even have cracks in walls. Apart from fine cracks due to shrinkage, cracks in plaster are always indicative of structural cracking of the wall.

In the author's opinion, these changes in CIS-64 scale were deliberately introduced in IS 1893-2002 to be consistent with the dubious intent of permitting the construction of seismically most vulnerable Type A structures even in the severest seismic zone (zone V) of India. With these changes, structural damage and life-threatening damage starts from Grade 4. Without these changes, structural damage would have commenced from Grade 2 and life-threatening damage from Grade 3.

It is surprising that BIS should have continued to use CIS-64 in its latest revision of IS 1893 in 2002, even though a more comprehensive and more precise European Macro-seismic Scale 1998 with international approval was available (ESC, 1998). BIS has retained CIS-64 in IS 1893-2002 so that the life-loss potential of seismically vulnerable constructions in highly seismic areas of the country appears to be lower than what it would appear if EMS-98 (ESC, 1998) had been used. This conclusion emerges if we compare CIS-64 with EMS-98 regarding the seismic intensities at which the different types of structures experience structural damage and total collapse. In EMS-98, Grade 2 and Grade 3 damages have the following descriptions.

<table>
<tr><th colspan="2">Description in EMS-98 for Grade 2: Moderate Damage
(Slight Structural Damage, Moderate Non-structural Damage)</th></tr>
<tr><td>In Masonry Buildings</td><td>In Reinforced Concrete Buildings</td></tr>
<tr><td>Cracks in many walls; Fall of fairly large pieces of plaster; Partial collapse of chimneys.</td><td>Cracks in columns and beams of frames and in structural walls; Cracks in partition and infill walls; fall of brittle cladding and plaster; Falling mortar from the joints of wall panels.</td></tr>
<tr><th colspan="2">Description in EMS-98 for Grade 3: Substantial to Heavy Damage
(Moderate Structural Damage, Heavy Non-structural Damage)</th></tr>
<tr><td>In Masonry Buildings</td><td>In Reinforced Concrete Buildings</td></tr>
<tr><td>Large and extensive cracks in most walls; Roof tiles detach; Chimneys fracture at the roof line; Failure of individual non-structural elements (partitions, gable walls).</td><td>Cracks in columns and beam column joints of frames at the base and at joints of coupled walls; Spalling of concrete cover, buckling of reinforced rods; Large cracks in partition and infill walls, failure of individual infill panels.</td></tr>
</table>

Thus, if EMS-98 or the CIS-64 given in pre-2002 IS 1893 standards had been used, then structural damage would have commenced at Grade 2, and life-threatening damage would have commenced at Grade 3.

As per IS 1893-2002, the CIS-64 intensities at which structural damage (Grade 4) and total collapse (Grade 5) occur in buildings are listed as follows:

Type of Structure	**For Structural Damage (Grade 4 Damage)**	**For Total Collapse (Grade 5 Damage)**
Type A	To a few in Intensity VII (Zone III) To most in Intensity VIII (Zone IV)	To many in Intensity IX (Zone V) To most in Intensity X (Zone V)
Type B	To a few in Intensity VIII (Zone IV) To many in Intensity IX (Zone V)	To a few in Intensity IX (Zone V) To many in Intensity X (Zone V)
Type C	To a few in Intensity IX (Zone V) To many in Intensity X (Zone V)	To a few in Intensity X (Zone V)

Thus, as per CIS-64, even the seismically most vulnerable Type A structures (i.e., buildings in fieldstone, rural structures, un-burnt brick houses, clay houses) can be expected to escape any structural damage in Zones I and II. Type B structures can be expected to escape any structural damage in Zones I, II and III and Type C structures in Zones I, II, III and IV. Further, none of Type A, B or C structures can be expected to suffer total collapse in Zones I, II, III and IV. However, in Zone V, no type of building, whether of Type A, B or C, is completely safe from total collapse. Accordingly, IS 1893 does not place any restriction on the type of buildings that can be constructed in any seismic zone. Therefore, according to BIS, the emphasis in India should be to seismically upgrade Type A buildings in Zones III, IV and V; Type B buildings in Zones IV and V; and, Type C buildings in Zone V so that life-loss may be reduced in a particular intensity of seismic ground shaking. With this objective, BIS has published IS 13827 and IS 13828 for Type A structures; IS 4326 for Type B and Type C structures; and, IS 13920 for Type C structures. Section 1 titled "Scope" in IS 13827 (on earthen buildings) and IS 13828 (on low-strength masonry buildings) confirm this objective of BIS and read as follows (with author's emphasis):

Clause 1.2 in IS 13827-1993	***Clause 1.1.1 in IS 13828-1993***
The provisions of this standard are applicable in seismic Zones III, IV and V. No special provisions are considered necessary for buildings in seismic Zones I and II.	The provisions of this standard are applicable in seismic Zones III to V. No special provisions are considered necessary for buildings in seismic Zones I and II.

Thus, BIS clearly promotes the construction of seismically most vulnerable Type A structures in the seismically most vulnerable Zone V of India. This is irrespective of the immense life-loss that has occurred in such structures during past earthquakes even in the seismically least vulnerable Zone I (e.g. Latur Killari Earthquake of 1993) of India. That BIS does not consider life-safety as a criterion for earthquake resistant design of structures is amply made clear by issuance of the following half-hearted warnings in the note(s) that appear immediately after the "Scope" as above.

Notes in IS 13827-1993	***Note in IS 13828-1993***
1. Earthen buildings are inherently weak against water and earthquakes and should preferably be avoided in flood prone, high rainfall areas and seismic zones IV and V. 2. Attention is hereby drawn to the fact that earthen construction as dealt with herein will neither qualify as engineered construction nor totally free from collapse in severe seismic intensities VIII and IX on MMI scale. However, inclusion of special design and construction features as recommended in this standard will raise their weather and seismic resistance appreciably, reducing greatly the chances of collapse even in such seismic intensities.	Attention is hereby drawn to the fact that low-strength masonry as dealt with herein will neither qualify as engineered construction nor totally free from collapse in severe seismic intensities VIII or IX. However, inclusion of special design and construction features provided herein will raise their seismic resistance appreciably, reducing greatly the chances of collapse even in such seismic intensities.

Even these warnings do not warn about possible life-loss, but only of 'collapse'. By stating that these constructions do not qualify as engineered constructions, BIS merely seeks to absolve itself, and the Government of India, of any culpability in case of their damage during an earthquake. It also calls IS 13827 and IS 13828 merely as "Guidelines" rather than "Code of Practice" with the same intent.

However, if EMS-98 intensity scale were used, a totally different picture emerges. The intensities at which structural damage (Grade 2), life-safety (Grade 3) and total collapse (Grade 5) occur in buildings as per EMS-98 are listed as follows:

Type of Structure	**Grade 2 Damage (Onset of Structural Damage)**	**Grade 3 Damage (Onset of Life-Threatening Damage)**	**Grade 5 Damage (Total Collapse)**
Type A	To a few in Intensity VI (Zone II) To most in Intensity VII (Zone III)	To many in Intensity VII (Zone III) To most in Intensity VIII (Zone IV)	To a few in Intensity VIII (Zone IV) To many in Intensity IX (Zone V) To most in intensity X (Zone V)
Type B	To a few in Intensity VI (Zone II) To many in Intensity VII (Zone III)	To a few in Intensity VII (Zone III) To many in Intensity VIII (Zone IV)	To a few in Intensity IX (Zone V) To many in Intensity X (Zone V)
Type C	To a few in Intensity VII (Zone III)	To a few in Intensity VIII (Zone IV) To many in Intensity IX (Zone V)	To a few in Intensity X (Zone V)

EMS-98 clearly states that earthquake resistant features (as given in IS 13827, IS 13828 and IS 4326 and IS 13920) in Type A, B and C structures can, in exceptional cases, at most shift their vulnerability type up one level. As per EMS-98, for life-safety it would be necessary to avoid Grade 3 damages. That would prohibit Type A structures with or without earthquake resistant provisions in seismic Zones III, IV and V. It would also prohibit Type B structures with or without earthquake resistant provisions in Zones IV and V; and Type C structures with or without earthquake resistant provisions in Zone V.

However, even the mapping of seismic zones with seismic intensities given in IS 1893 can be easily challenged. The Latur-Killari 1993 earthquake (*M* 6.4, about 8000 officially dead, maximum intensity of shaking VIII-IX on MM scale as per EERI (2002), Page 324) occurred in Zone I (i.e. in an intensity V area as per IS 1893-1984), and killed a large number of people in seismically vulnerable type A structures. As per IS 13827 and IS 13828, for seismic Zones I (intensity V areas) and II (intensity VI areas), no seismic considerations are required even for such structures. Thus, BIS is culpable for all the damages and life-loss that occurred in this earthquake. It is obvious from the total collapse of a large number of type A structures in this earthquake that the maximum intensity of at least VIII occurred in this region. BIS anticipated that such earthquakes could occur, and while mapping seismic zones to intensities, IS 1893-1970 and IS 1893-1975 issued the following half-hearted and self-contradictory disclaimer in Clause 0.6 to absolve itself, and the Government of India, of any culpability (with author's emphasis): "…These limits of intensity have been recommended for the purpose of design but these limits need not necessarily be always the highest intensity that would occur anywhere within the given zone. It is possible in some cases that earthquakes of much higher intensity may occur at any particular spot, which is unpredictable. The probabilities, however, are that a structure designed on the assumption that intensity indicated for each zone is about the maximum that is likely to occur, would ensure a reasonable amount of safety."

The Latur-Killari 1993 earthquake showed that Zone I areas should have been mapped to at least intensity VII, if not to intensity VIII, rather than to intensity V. As per CIS-64 in intensity VII areas, the following damage occurs: "In many buildings of Type C damage of Grade 1 is caused; in many buildings of Type B damage is of Grade 2. Most buildings of Type A suffer damage of Grade 3, few of Grade 4. …"

Thus, if BIS had mapped Zone I to intensity VII rather than to intensity V, then much of the life loss in Type A structures during the Latur-Killari 1993 earthquake could have been prevented, because such a mapping would have mandated the seismic upgradation of Type A structures according to the provisions of IS 13827 and IS 13828. Rather than mapping the entire Zone I to intensity VII, BIS in IS 1893-2002 has chosen to abolish Zone I by merging the Zone I areas into Zone II, and it has mapped the Latur-Killari region to Zone III (intensity VII area). With these changes, the enlarged Zone II has become the region of least seismicity and seismically most vulnerable Type A structures can continue to be constructed in this zone even without observing the earthquake resistant provisions of IS 13827 and IS 13828. Such structures are fated to cause immense life-loss during the next Latur-Killari type earthquake in those zones.

If the seismic zoning given in IS 1893-2002 is taken to represent relative seismicities in India, then the mapping of seismic zones to intensities needs to be notched up by at least one intensity level. With this, Zones II, III, IV and V would correspond to intensities VII or less, VIII, IX, X and above, respectively. Life-safety would then mandate, that Type A and B structures be prohibited in seismic Zones II, III, IV and V, i.e. in the entire country; and, Type C be prohibited in Zones III, IV and V. With earthquake resistant features (as per IS 4326, IS 13827, IS 13828 and IS 13920), however, Type A structures may be permitted in Zone II, Type B in Zones II and III and Type C in Zones III and IV. For Zones IV and V, structure types that are less vulnerable than Type C structures with earthquake resistant features would be required. EMS-98 classifies them as Type D, E and F structures, as follows:

Type D Structures	Reinforced or confined masonry structures, structures having reinforced concreted frames with moderate level of earthquake resistant design, structures having reinforced concreted shear walls with moderate level of earthquake resistant design, timber structures.
Type E Structures	Structures having reinforced concrete frames with high level of earthquake resistant design, structures having reinforced concrete shear walls with high level of earthquake resistant design, steel structures.
Type F Structures	Exceptionally well-built Type E structures.

In India, with the exception of timber structures built more than about 50 years ago, there are virtually no Type D, Type E or Type F structures in existence. If EMS-98 had been used in IS 1893-2002 instead of a surreptitiously modified CIS-64, then it would have at least created some awareness in India about the existence of such structures in other countries and would have motivated the construction of such types of earthquake resistant structures.

From the above discussion, it is obvious that use of CIS-64 rather than EMS-98, mapping of seismic zones to lower intensities, and not taking “life-safety” as a criterion for earthquake resistant design in IS 1893 are intended to promote the construction of seismically most vulnerable Type A structures in all seismic zones of India, albeit with some earthquake resistant features in Zones III, IV and V. This dubious intent has arisen owing to the need to ensure seismically “safe” housing to the people of India at a cost they can afford. Even earthquake disasters have failed to weaken this intent, because after every earthquake the government desires to get the affected people rehabilitated in seismically “safe” housing at the minimum possible cost to itself. Unfortunately, this intent has resulted in lowering of seismic standards in India to levels much below that of developed countries and a false sense of security. If Type A non-engineered constructions are projected as adequately safe in Zone V, then Type B and Type C structures must be even safer; and, India appears as a seismically very safe place. That is why lessons learned from past earthquake disasters are yet to be adequately reflected in Indian seismic codes and this poses a serious obstacle to the emergence of PBE in India, and that is why the author repeatedly dwells on this theme in this paper.

In US, building performance levels are divided into structural performance levels (SP-1 thru SP-6) and nonstructural performance levels (NP-A thru NP-E), and then a combination of structural and nonstructural performance levels is set as the performance objective to be met at a given level of earthquake. These combinations can be approximately mapped to the damage grades specified in EMS-98 as follows:

Damage Grade as per EMS-98	**Approximate Building Performance Combination in PBE**
Grade 1 (no structural damage, slight nonstructural damage)	SP-1 (immediate occupancy) + NP-A (operational) = 1-A (operational)
Grade 2 (slight structural damage, moderate nonstructural damage)	SP-1 (immediate occupancy) + NP-B (immediate occupancy) = 1-B (immediate occupancy)
Grade 3 (moderate structural damage, heavy nonstructural damage)	SP-3 (life safety) + NP-C (life safety) = 3-C (life safety)
Grade 4 (heavy structural damage, very heavy nonstructural damage)	SP-5 (structural stability) + NP-E (not considered) = 5-E (structural stability)
Grade 5 (very heavy structural damage)	SP-6 (not considered) + NP-E (not considered) = 6-E (not considered)

In the author’s opinion, it would be desirable to develop a Macro-seismic Intensity Scale, encompassing all types of structures, for seismic damage surveys as well as for setting the performance objectives and evaluation criteria under PBE in India. EMS-98 offers a very good base for the development of such a scale. Such a scale would enable a quick validation of the effectiveness of PBE procedures in future earthquakes.

In India, IS 1893-1962, IS 1893-1966, IS 1893-1975 and IS 1893-1984 actually specified only one level of earthquake loading for use in the force-method of design, even though the stated performance objective specified two levels of earthquake ground shaking intensities – moderate and heavy. IS 1893-2002 specifies two levels of earthquakes – Maximum Considered Earthquake (MCE) and Design Basis Earthquake (DBE). In Clause 6.1.3, it states the performance objective as follows: “The design approach adopted in this standard is to ensure that structures possess at least a minimum strength to withstand minor earthquakes (< DBE), which occur frequently, without damage; resist moderate earthquake (DBE) without significant structural damage though some nonstructural damage may occur; and aims that structures withstand a major earthquake (MCE) without collapse.”

From the above, it appears that a three level performance objective is intended. However, minor earthquakes are very imprecisely defined as “< DBE”. Also the terms describing the damage are not consistent with those used in the Intensity Scale. Corresponding to DBE, for example, the term, “without significant structural damage” may be taken to mean Grade 2 (slight structural damage) or Grade 3 (moderate structural damage); but the term “some nonstructural damage” seems to correspond to Grade 1 (slight nonstructural damage). Thus, what grade of damage is implied at DBE is not clear. Similarly corresponding to MCE, the term “without collapse” may be taken to correspond to Grade 3 (if even partial collapses at Grade 4 damage level are to be avoided) or to Grade 4 damage states (if merely total collapse at Grade 5 is to be avoided).

In PBE, merely stating a performance objective is not sufficient; it has to be followed up by analyses or a methodology for ensuring that the stated performance objectives will indeed be met by the evaluated structures. PBE thus requires much tighter language and cross-referencing to be used in the specifications. The following two-level performance objective is suggested for new ordinary structures.

- Under DBE, damage must be limited to Grade 2 (slight structural damage, moderate nonstructural damage) in order to enable Immediate Occupancy after DBE.
- Under MCE, damage must be limited to Grade 3 (moderate structural damage, heavy nonstructural damage) in order to ensure Life Safety after MCE.

For evaluation of existing ordinary structures, the following two-level performance objective is suggested.

- Under DBE, damage must be limited to Grade 3 (moderate structural damage, heavy nonstructural damage) in order to ensure Life Safety after DBE.

- Under MCE, damage must be limited to Grade 4 (heavy structural damage, very heavy nonstructural damage) in order to ensure Structural Stability after MCE.

For important structures, i.e. essential and hazardous facilities, higher performance objective will need to be specified.

CONSIDERATION OF SITE SOIL CONDITIONS IN INDIAN SEISMIC CODE

IS 1893-1962 and IS 1893-1966 divided the country into seven seismic zones, Zone 0 to Zone VI, and the seismic coefficient method was specified for three soil types, as shown in Table 2.

Table 2: Horizontal Seismic Coefficient (α_k) as per IS 1893-1962 and IS 1893-1966

Zone No.	Horizontal Seismic Coefficient (α_k) for		
	Soil Type I (Hard soils having a bearing capacity of 45 t/m^2)	Soil Type II (Average soils having a bearing capacity between 20 and 45 t/m^2)	Soil Type III (Soft soils having a bearing capacity of less than 20 t/m^2)
VI	0.08	0.10	0.12
V	0.06	0.08	0.10
IV	0.05	0.06	0.08
III	0.04	0.05	0.06
II	0.02	0.03	0.04
I	0.00	0.01	0.02
0	0.00	0.00	0.00

Beginning with IS 1893-1970, the number of seismic zones was reduced to five by merging Zone 0 with Zone I, and Zone VI with Zone V. The horizontal seismic coefficients, specified in IS 1893-1970, IS 1893-1975 and IS 1893-1984, are shown in Table 3.

Table 3: Horizontal Seismic Coefficient (α_k) as per IS 1893-1970, IS 1893-1975 and IS 1893-1984

Zone No.	Horizontal Seismic Coefficient (α_k)
V	0.08
IV	0.05
III	0.04
II	0.02
I	0.01

The seismic coefficients in Table 3 correspond to the values given in Table 2 for hard soils for Zones VI, IV, III and II. To increase the seismic coefficient for other soil types, a multiplying factor β depending upon the soil foundation system was introduced, with values shown in Table 4.

Table 4: Values of Soil-Foundation System Factor (β) as per IS 1893-1970, IS 1893-1975 and IS 1893-1984

Soil Type	Values of β for			
	Bearing Piles Resting on Type I Soils or Raft Foundations	Friction Piles, Combined or Isolated RCC Footings with Tie Beams	Isolated RCC Footings without Tie Beams or Unreinforced Strip Foundations	Well Foundations
I – Hard Soils	1.0	1.0	1.0	1.0
II – Medium Soils	1.0	1.0	1.2	1.2
III – Soft Soils	1.0	1.2	1.5	1.5

With the maximum value of this factor, 1.5, the maximum horizontal seismic coefficient for Zone V becomes 1.5 × 0.08 = 0.12, which is identical for soft soils in Zone VI of IS 1893-1962 and IS 1893-1966.

The factor β obscured the fact that the seismic coefficient depended on the site soil-profile between 1970 and 2002. In IS 1893-2002, the spectral accelerations once again depend on the site soil conditions, as shown in Table 5.

Thus, for the constant velocity region of the spectrum, the amplification factors for medium and soft soil sites are 1.36 and 1.67, respectively. Compare these values with implied amplifications of $0.08/0.06 = 1.33$ for average soils and $0.10/0.06 = 1.67$ for soft soils given for Zone V in IS 1893-1962. How little has changed in 40 years!

Table 5: Effect of Soil Conditions on Spectral Accelerations as per IS 1893-2002

For Type I Rocky or Hard Soil Sites: These are the soils having standard penetration value, $\overline{N}$ > 30.	$\frac{S_a}{g} = \begin{cases} 1+15T & 0.00 \le T \le 0.10 \\ 2.50 & 0.10 \le T \le 0.40 \\ 1.00/T & 0.40 \le T \le 4.00 \end{cases}$
For Type II Medium Soil Sites: These are the soils with 10 < $\overline{N}$ < 30.	$\frac{S_a}{g} = \begin{cases} 1+15T & 0.00 \le T \le 0.10 \\ 2.50 & 0.10 \le T \le 0.55 \\ 1.36/T & 0.55 \le T \le 4.00 \end{cases}$
For Type III Soft Soil Sites: These are all soils with $\overline{N}$ < 10.	$\frac{S_a}{g} = \begin{cases} 1+15T & 0.00 \le T \le 0.10 \\ 2.50 & 0.10 \le T \le 0.67 \\ 1.67/T & 0.67 \le T \le 4.00 \end{cases}$

Note: The description of soil types in the above table is different from that given in IS 1893-1962 and IS 1893-1966 wherein the soils were classified according to allowable bearing capacity. The above description can be traced to IS 1893-1970.

Table 6 maps the soil sites given in ATC-40, FEMA 302 and FEMA 356 to those given in IS 1893-2002. Table 7 then compares the computed values of acceleration based site coefficient, F_a, and velocity-based site coefficient, F_v, for various seismic zones given in IS 1893-2002 using FEMA 302 specifications to their implied values as per IS 1893-2002.

Table 6: Mapping of Soil Sites given in FEMA 302 to those given in IS 1893-2002

Site Class	Description	Shear Wave Velocity $\overline{v}_s$ (m/s)	SPT Value	Corresponding Site Type as per IS 1893-2002
A	Hard rock	$\overline{v}_s$ > 1500	Not Applicable	Type I rocky or hard soil sites
B	Rock	760 < $\overline{v}_s$ ≤ 1500	Not Applicable	Type I rocky or hard soil sites
C	Very dense soil and soft rock	360 < $\overline{v}_s$ ≤ 760	$\overline{N}$ > 50	Type I rocky or hard soil sites
D	Stiff soil	180 < $\overline{v}_s$ ≤ 360	15 ≤ $\overline{N}$ ≤ 50	Partly Type I rocky or hard soil sites for 30 < $\overline{N}$ and partly Type II medium soil sites for 15 ≤ $\overline{N}$ ≤ 30
E	Soft soil	$\overline{v}_s$ ≤ 180	$\overline{N}$ < 15	Partly Type II medium soil sites for 10 ≤ $\overline{N}$ ≤ 15 and partly Type III soft soil sites for $\overline{N}$ < 10
F	Very soft soil, requiring site-specific evaluations			Type III soft soil sites

Table 7 shows that the implied values of F_a and F_v are underestimated in IS 1893-2002 by about 2.5 for soft soils as compared to FEMA 302.

The Kutch Earthquake of 26th January 2001 caused heavy damage and destruction to hundreds of multistoried buildings far away from the earthquake epicenter. Most of these buildings had weak and soft ground stories used for parking and were also situated on soft soil sites. For example, buildings in Ahmedabad (epicentral distance > 250 km) were situated on Sabarmati river deposits; in Surat (epicentral distance > 350 km) on Tapi river deposits; and, in Gandhidham and Kandla (epicentral distance > 50 km) on marine deposits. Similar buildings on stiffer soil-sites, in same cities or in other cities, closer to the epicentre, remained unscathed. This observation could not have escaped the attention of any structural engineer, familiar with the damage that occurred during 1985 Mexico Earthquake, and yet BIS chose to consider it inadequately in IS 1893-2002, despite the availability of ATC-40, FEMA 273, FEMA 302 and FEMA 356 documents!

Table 7: Comparison of F_a and F_v Values between FEMA 302 and IS 1893-2002

		Zone as per IS 1893-2002				
		II	**III**	**IV**	**V**	
Zone Factor, *Z*		0.10	0.16	0.24	0.36	
Short-Period Spectral Acceleration, S_s (*g*'s) = 2.5*Z* as per IS 1893-2002		0.25	0.4	0.6	0.9	**Implied Value of F_a as per IS 1893-2002 for All Zones**
F_a as per FEMA 302 for	**Site Class A**	0.8	0.8	0.8	0.8	1.0
	Site Class B	1.0	1.0	1.0	1.0	1.0
	Site Class C	1.2	1.20	1.16	1.04	1.0
	Site Class D	1.6	1.48	1.32	1.14	1.0
	Site Class E	2.5	2.02	1.50	1.02	1.0
	Site Class F	Requires site specific geotechnical investigations				1.0
1-sec Period Spectral Acceleration, S_1 (*g*'s) for Site Class B, i.e., Type I Soil of IS 1893-2002		0.10	0.16	0.24	0.36	**Implied Value of F_v as per IS 1893-2002 for All Zones**
F_v as per FEMA 302 for	**Site Class A**	0.8	0.8	0.8	0.8	1.0
	Site Class B	1.0	1.0	1.0	1.0	1.0
	Site Class C	1.7	1.64	1.56	1.44	1.0
	Site Class D	2.4	2.16	1.92	1.68	1.0 for $\overline{N} > 30$ and 1.36 for $15 \le \overline{N} \le 30$
	Site Class E	3.5	3.32	3.04	2.56	1.36 for $10 \le \overline{N} \le 15$ and 1.67 for $\overline{N} \le 10$
	Site Class F	Requires site specific geotechnical investigations				1.67

DESIGN BASE SHEAR FOR BUILDINGS IN INDIAN SEISMIC CODE

IS 1893-1962, IS 1893-1966 and IS 1893-1970 had only one method to compute the value of base shear for buildings, i.e. the seismic coefficient method (Tables 2 and 3). IS 1893-1975 and IS 1893-1984 also specify the response spectrum method as an alternative way of computing the design base shear. In fact, the two methods give identical values for 5% damping ratio. IS 1893-1984 also introduced a "structure performance factor", *K*, to increase the seismic loads by 60% for buildings with Ordinary Moment Resisting Frames (OMRF) and Ordinary Shear Wall Frames and $K = 1.6$ was specified. For buildings with Special (i.e. ductile) Moment Resisting Frames (SMRF) and Special Shear Wall Frames, there was no increase and $K = 1.0$ was specified.

IS 1893-2002 gives the following expression for computing the design base shear, V_B, for a building:

$$V_B = A_h W \tag{1}$$

Here, W is the seismic weight of the building and $A_h\,(= V_B/W)$ is the design horizontal seismic coefficient computed by the following expression:

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g} \tag{2}$$

in which Z is the zone factor for MCE (Z = 0.36, 0.24, 0.16 and 0.10 for Zones V, IV, III and II, respectively), the factor 2 in the denominator of Z is used to reduce MCE zone factor to DBE zone factor, I is the importance factor (I = 1.0 for ordinary buildings and 1.5 for important service and community buildings), R is the response reduction factor (R = 3 for reinforced concrete buildings with ordinary moment resisting frames (OMRF), i.e. those not meeting the ductile detailing requirements of IS 13920-1993, and R = 5 for reinforced concrete buildings with special moment resisting frames (SMRF), i.e. those meeting the ductile detailing requirements of IS 13920-1993), and S_a/g is the average response acceleration coefficient with a maximum value 2.5 in the short period range for all site-soils.

The values of design horizontal seismic coefficient (V_B/W) as per IS 1893-1962, IS 1893-1966, IS 1893-1970, IS 1893-1975, IS 1893-1984 and IS 1893-2002 are compared in Table 8 for the highest seismic zone for some representative conditions.

Table 8: Variation of Design Horizontal Seismic Coefficient in IS 1893 during 1962 to 2002

Year of IS 1893	**Design Horizontal Seismic Coefficient $A_h\,(= V_B/W)$ for Ordinary R/C Buildings (*I* = 1.0, 5% Damping) in Zone of Severest Seismicity for**					
	Short Period (*T* = 0.1 to 0.35 sec) Buildings Situated on			**A 10-Storied Building (Period, *T* = 1.0 sec) Situated on**		
	Hard Soil Sites	**Medium Soil Sites**	**Soft Soil Sites**	**Hard Soil Sites**	**Medium Soil Sites**	**Soft Soil Sites**
1962 (Zone VI)	0.08	0.10	0.12	0.025	0.031	0.038
1966 (Zone VI)	0.08	0.10	0.12	0.048	0.06	0.072
1970 (Zone V)	0.08	0.096	0.12	0.04	0.048	0.06
1975 (Zone V)	0.08	0.096	0.12	0.044	0.0528	0.066
1984 (Zone V)	0.128 for OMRF 0.08 for SMRF	0.1536 for OMRF 0.096 for SMRF	0.192 for OMRF 0.12 for SMRF	0.0704 for OMRF 0.044 for SMRF	0.0845 for OMRF 0.0528 for SMRF	0.106 for OMRF 0.066 for SMRF
2002 (Zone V)	0.15 for OMRF 0.09 for SMRF	0.15 for OMRF 0.09 for SMRF	0.15 for OMRF 0.09 for SMRF	0.06 for OMRF 0.036 for SMRF	0.082 for OMRF 0.049 for SMRF	0.10 for OMRF 0.06 for SMRF

Note: In computing the values for IS 1893-1970, IS 1893-1975 and IS 1893-1984, the value of soil-foundation system factor, β, has been taken as 1.0, 1.2 and 1.5 for hard, medium and soft soil sites, respectively. In IS 1893-1984, the structure performance factor, *K*, was introduced with a value of 1.6 for OMRF concrete buildings and 1.0 for SMRF concrete buildings. In IS 1893-2002, different acceleration spectra were specified for the three soil sites and *K* was replaced by Response Reduction Factor, *R*, with a value of 3 for OMRF concrete buildings and 5 for SMRF concrete buildings.

Most buildings in India are up to 4-stories, and the design horizontal seismic coefficient in short period range for OMRF is applicable for these. This value has essentially remained unchanged between

1962 and 1984. In 1984, this value increased by 60%. In 2002, it further increased by 17% for hard soil sites, remained essentially unchanged for medium soil sites, and decreased by 22% for soft soil sites.

Multistoried buildings in structural steel and with SMRF concrete frames are still very rare in India, and, therefore, only the values for design horizontal seismic coefficient for OMRF concrete buildings are really relevant. Multistoried buildings greater than 10 stories are also very rare in India. The design horizontal seismic coefficient for a 10-storied building remained unchanged from 1966 to 1984. In 1984, this value increased by 60%. In 2002, it decreased by 14% for hard soil sites and remained essentially unchanged for medium and soft soil-sites.

For non-building structures, such as elevated water tanks, chimneys, silos, bridges, dams, retaining walls, etc., the seismic coefficient method contained in IS 1893-1984 continues to be in use till date. The relevant values for these structures correspond to the values for SMRFs in Table 8, and they too have essentially remained unchanged since 1962.

Following the unacceptable and widespread damage during the Kutch Earthquake of 26th January 2001, it was expected that IS 1893-2002 would specify higher values of design horizontal seismic coefficient (V_B/W) compared to IS 1893-1984. But, this hope was belied as Table 9 comparing the values of design horizontal seismic coefficient in the two codes shows the maximum difference to be about ±20%. For most conditions, the two codes give essentially the same values.

Table 9: Values of Design Horizontal Seismic Coefficient in IS 1893-1984 and IS 1893-2002

Seismic Zone	Year of IS 1893	Design Horizontal Seismic Coefficient (V_B/W) for Ordinary Reinforced Concrete Buildings (I = 1.0, 5% Damping) with Ordinary Moment Resisting Frames for					
		Short Period (T = 0.1 to 0.35 sec) Buildings Situated on			A 10-Storied Building (T = 1.0 sec) Situated on		
		Hard Soil Sites	Medium Soil Sites	Soft Soil Sites	Hard Soil Sites	Medium Soil Sites	Soft Soil Sites
V	1984	0.128	0.1536	0.192	0.070	0.085	0.106
	2002	0.150	0.150	0.150	0.060	0.082	0.100
IV	1984	0.080	0.096	0.120	0.044	0.053	0.066
	2002	0.100	0.100	0.100	0.040	0.054	0.067
III	1984	0.064	0.077	0.096	0.035	0.042	0.053
	2002	0.067	0.067	0.067	0.027	0.036	0.045
II	1984	0.032	0.038	0.048	0.018	0.021	0.021
	2002	0.042	0.042	0.042	0.017	0.023	0.028

To obtain a perspective on these values, Table 10 compares the short-period spectral accelerations for MCE, DBE and OMRF buildings as per IS 1893-2002 for Zone V to the values for Maximum Earthquake (ME), Design Earthquake (DE) and Serviceability Earthquake (SE) as per ATC-40 for its Zones 4 and 3. These values are computed for 5% damping, site-soil class B of ATC-40 (which corresponds to Type I hard soil of IS 1893-2002) and for sites at least 15 km away from known seismic source.

Comparing columns 2 and 6 of Table 10, we find that MCE of IS 1893 corresponds to DE of ATC-40; and DBE of IS 1893 corresponds to SE of ATC-40. This shows that low values have been taken for the MCE and DBE earthquake levels in IS 1893-2002!

During the Kutch Earthquake of 26th January 2001, Peak Ground Acceleration (PGA) was estimated to be 0.64g at Anjar (Intensity IX as per Sinvhal et al., 2001a) on the basis of a Structure Response Record that gave a short-period spectral acceleration value of 1.6g for 5% damping ratio (Kumar et al., 2001). The PGA value for MMI X regions would have been even higher. Thus, the value of Z = 0.36, used for Zone V in IS 1893-2002, is very unconservative.

Table 10: Comparison of Short-Period Spectral Accelerations in IS 1893-2002 with ATC-40

As per IS 1893-2002 for Zone V (Z = 0.36)		As per ATC-40			
EQ Level	**S_S Value**	**EQ Level**	**S_S Value for its Zone 4 (Z = 0.40)**	**S_S Value for its Zone 3 (Z = 0.30)**	**Interpolated Value of S_S for Z = 0.36**
MCE	0.90*g*	ME	1.25*g*	1.125*g*	1.20*g*
DBE	0.45*g*	DE	1.00*g*	0.75*g*	0.90*g*
For OMRF (R = 3)	0.15*g*	SE	0.50*g*	0.375*g*	0.45*g*

ARE DUCTILE DESIGNS REQUIRED BY THE NEW INDIAN SEISMIC CODE?

Prior to emergence of PBE, the capacity design method to ensure a ductile design was well established. In India, BIS issued IS 13920-1993 (BIS, 1993d), the Code of Practice for Ductile Detailing of Reinforced Concrete Structures, in 1993. Its requirements are based on the capacity design method and require columns to be stronger than beams to prevent story mechanisms; shear strength sufficient in columns and beams to ensure plastic hinging in the beams; and, closely spaced ties with 135-degree hooks in columns and closely spaced stirrups with 135-degree hooks in beams to provide confinement to the concrete and prevent buckling of longitudinal bars. The provisions of this code are far more stringent than the provisions of IS 456-2000 (BIS, 2000), “Code of Practice for Plain and Reinforced Concrete”, which allows the beams to be stronger than the columns; 90-degree hooks, larger spacing and smaller diameters for ties and stirrups in columns and beams, respectively. Adherence to IS 13920 requires much greater quality control and implies a tremendous increase in the cost of the structure. To remain competitive, structural designers avoid adhering to provisions of IS 13920. They use structural performance factor K = 1.6 corresponding to buildings with non-ductile reinforced concrete frames, rather than the value of 1.0 for buildings with ductile reinforced concrete frames. The scope of IS 13920-1993 is stated in Clause 1.1.1 as follows (with author’s emphasis): “Provisions of this code shall be adopted in all reinforced concrete structures which satisfy one of the following four conditions: (a) the structure is located in seismic Zone IV or V; (b) the structure is located in seismic Zone III and has the importance factor (I) greater than 1.0; (c) the structure is located in seismic Zone III and is an industrial structure; and (d) the structure is located in seismic Zone III and is more than 5 stories high.”

As IS 13920 was issued in 1993, it was neither referred nor its scope confirmed in IS 1893-1984, and that explained the use of K = 1.6 by structural designers to escape from the scope of IS 13920.

A very large number (~117) of apartment buildings, constructed in Ahmedabad after 1993, had weak and soft ground stories used for parking cars and suffered unacceptable damage and destruction during the Kutch Earthquake of 26th January 2001. These apartment buildings (Importance Factor 1.0) in Ahmedabad (seismic Zone III) had only 5 stories and did not attract the stringent provisions of IS 13920-1993. Therefore, once again, the seismic codes of India were found culpable for most of the damage in this earthquake!

One way of bringing multistoried apartment buildings within the scope of IS 13920-1993 for Zone III would have been to assign them an importance factor of 1.5 considering that they have several residential units with life-loss potential similar to schools and community halls, for which I = 1.5 is specified. IS 1893-2002 specifies I = 1.0 for multistoried apartment buildings and merely notes that I = 1.5 “may” be used depending on economy and strategy considerations.

Subsequently, the scope of IS 13920 has been altered so that its provisions are mandated for all reinforced concrete structures in seismic Zones III, IV and V. It was hoped that after publication of IS 1893-2002, structural designers would be obliged to follow IS 13920 in these zones. Surprisingly, IS 1893-2002 also does not confirm the scope of IS 13920-1993 and permits buildings with OMR frames or dual systems with ordinary shear walls plus OMR frames in all seismic zones. It only prohibits buildings with ordinary reinforced concrete shear walls in seismic Zones IV and V, even though such buildings are known to withstand earthquakes better than buildings with OMR frames. Therefore, structural designers are still not obliged to follow the provisions of IS 13920 for ductile design after publication of IS 1893-2002!

WHY DOES INDIA NEED TO EMBRACE PERFORMANCE-BASED ENGINEERING NOW?

The seriously flawed seismic standards in India did not result in large-scale damage to engineered structures and served India rather well until 1991, because of the following reasons.

1. Till that time the poor economic situation did not permit much construction activity. There was severe shortage of structural steel and cement in the country; residences of one or two-stories were constructed for self-occupation only; office buildings were restricted to three stories and built by government agencies that could take a conservative view of the seismic code provisions; and multistoried apartments built by private construction companies were almost non-existent. Wherever possible, mud was used as mortar in load bearing walls of unreinforced brick masonry, even in government constructed residences. Steel was used only in floors and as minimal reinforcement in the form of lintel and gable bands in masonry walls. These building tended to be stiff with short-periods of vibration and, fortunately were vulnerable to near earthquakes only.
2. Fortunately in India, the zone of severest seismicity (Zone V as per IS 1893) comprised the mountainous region of Himalayas and the arid and marshy region of Kutch in Gujarat, both of which, until recently, had low population density and absence of urban infrastructure.
3. Short-period structures on soft soil sites not prone to liquefaction tend to be less vulnerable, because such soils attenuate the short-period seismic waves that pass through them. Thus, the thickly populated alluvium plains of Ganga-Yamuna river basin, lying in seismic Zones III and IV to the south of the seismically active Himalayas, have no public memory of earthquake damage.
4. Only earthquakes of around magnitude 6 are expected elsewhere in India, and engineered structures were expected to be relatively robust against these compared to the non-engineered structures.

All earthquakes, prior to the Kutch Earthquake of 26th January 2001, had only managed to highlight the large-scale destruction of seismically most vulnerable rural houses in random rubble stone masonry. Such construction was simply far more abundant (> 80% of all construction) in the highly seismic Himalayas and Kutch regions, as well as in the seismically least active Deccan plateaus of southern India where earthquakes of magnitude 6 occurred at long intervals. Other types of structures did get damaged, but on a much smaller scale compared to houses in random rubble stone masonry.

Owing to above reasons, the role of earthquake engineers in India was in practice confined to suggesting earthquake resistant features for seismically vulnerable rural houses or for offering consultation for the few major dams, major bridges and nuclear power plants that were to be constructed in India. For other structures of intermediate category, the role of architects and civil engineers not particularly knowledgeable about earthquake engineering was deemed to be sufficient. The Government of India, therefore, created the Department of Earthquake Engineering (DEQ) at Roorkee to provide consultation on major civil engineering projects; to prepare guidelines for earthquake resistant rural housing and for their strengthening and repair (ISET, 1981; BIS, 1993b, 1993c, 1993e); and to prepare the seismic code (IS 1893) to be followed for the remaining structures of intermediate category. Architects and civil engineers followed these as best as they could without understanding the goals, principles and philosophy of earthquake resistant design about which they had no formal education.

In 1991, however, India had to reluctantly abandon the failed socialist model of economy with its emphasis on self-reliance, government ownership and local markets in order to embrace the capitalist model of economy with its emphasis on interdependence among nations, private entrepreneurship and global markets. As a result, the bureaucratic controls of the government were gradually relaxed and private enterprise and economy began to thrive. The economic development led to a rapid increase in the number of cars and demand for apartments in towns and cities. Most of these apartment buildings tended to have weak and soft ground stories and/or basements for car parking. In some cities, firm soil sites were scarce, and land was reclaimed from the river flood plains and lakes to construct these apartments. As could be expected, such apartment buildings proved to be seismically far more vulnerable compared to houses in random rubble stone masonry during the Kutch Earthquake of 26th January 2001. These buildings were damaged up to 300 km away from the epicenter, whereas the damage to random rubble stone houses was restricted to about 30 km from the epicenter.

This earthquake showed that the seismic standards and practices followed hitherto were simply inadequate for economically resurgent India. In the global market economy, national standards need to be in tune with each other and International Standards must gradually evolve. Private construction companies function in a competitive environment and cannot be expected to interpret seismic standard conservatively as such interpretations are not conducive to profit making and survival. The concept of national standards serving as minimum standards to be followed is obsolete in the new economy.

Indian Standards based on PBE can easily be made by learning from the experience and building standards of USA and by using modern communication technologies for tapping the expertise available within and outside the country. However, a much bigger challenge is to improve the quality and rigour of civil engineering education, without which modern building codes based on PBE cannot be implemented. This is discussed in the next section.

WHY IS CIVIL ENGINEERING EDUCATION FLAWED IN INDIA AND HOW TO REMEDY IT TO FURTHER THE CAUSE OF PERFORMANCE-BASED ENGINEERING?

The Project Implementation Plan of NPEEE (NPEEE, 2003) describes the status of 'Earthquake Engineering Education in India' as follows:

> "Formal activities in the field of Earthquake Engineering in the country were started in the late 1950s at the University of Roorkee (UOR). The first Indian seismic code was published by the Bureau of Indian Standards in 1962. Since then, Indian earthquake engineers have handled numerous prestigious and challenging projects in high seismic regions of the country. However, an average civil engineer in the country has not been systematically brought into the agenda of earthquake safety yet. Our engineering curricula did not incorporate components related to earthquake resistant constructions, and we did not make serious systematic efforts to ensure that the practicing professional engineers are trained in this subject. As a result, a typical engineer even today looks at earthquake engineering as an area of super-speciality to be handled only by researchers and professors. The cause of earthquake-disaster mitigation through constructions that can appropriately withstand earthquakes can be achieved only when the professional civil engineers in India are able to ensure earthquake-resistant constructions.
>
> A typical undergraduate civil engineering curriculum in the county does not include any coverage of earthquake engineering. Even at the post-graduate level, only a small fraction of structural engineering students gets a chance to study earthquake engineering and design. This results in most civil engineers not receiving any formal training in earthquake engineering during the undergraduate or post-graduate studies. This anomaly needs to be corrected for a country like ours with an enormous earthquake problem.
>
> Even if we were to implement revised curricula in our institutions with adequate coverage of earthquake engineering principles, it may not be effective till we have sufficient number of qualified teachers of the subject, course materials, manuals, text books, etc. Hence, the entire issue of earthquake engineering education in India is fairly involved."

The prospects of adding the needed elements of earthquake engineering to the bachelor's curricula for civil engineers are brightest at the Indian Institute of Technology Roorkee (IITR), owing to presence of the Department of Earthquake Engineering (DEQ) here.

The absence of earthquake engineering coverage in undergraduate civil engineering curriculum was the unintended consequence of the decision to create the Department of Earthquake Engineering at Roorkee. The DEQ offers post-graduate degrees with specializations in Structural Dynamics and Soil Dynamics. Consequently, the curricula at the Department of Civil Engineering at Roorkee gradually became devoid of elements of earthquake engineering. Because, this department served as the role model for civil engineering departments at other institutions, their curricula also became devoid of elements of earthquake engineering.

Few practicing civil engineers get a Master's degree in Structural Engineering. Even during these studies, the courses in engineering seismology, soil dynamics and structural dynamics are not offered. As a result, these Civil Engineers too do not get the exposure to the needed elements of earthquake engineering. However, this is not the only issue relevant for PBE.

In late 1960s, Ph.D. degree, and in mid-1980s, research publications became necessary for career advancement for teachers. These degrees and research tended to be in computer analyses using finite elements, rather than in construction or design. Consequently, faculty interest in construction and design declined. Design courses were gradually replaced by analyses courses. Design courses limited their scope to design and optimization of structural members. In earlier times, design and optimization of complete structural systems could be covered, because the design process was simpler with fewer load combinations and working stress method of design.

Another unintended fallout of the increased research requirements was that teaching became a tertiary activity in all our engineering institutions. Consequently, the time-consuming and strenuous training components of engineering education have been almost sequentially eliminated during the past 40 years from the engineering curricula in the following order – off-campus field training, on-campus field training, practicals and tutorials. Consequently, drafting of structural drawings and practical training in construction got eliminated from the curriculum. Courses now have either no tutorials or maximum of one-hour tutorial per week. This has considerably reduced student-teacher interaction and weakened the students' grasp of fundamentals; and, resulted in a sharp decline in the rigour of civil engineering education. Unfortunately, this loss of rigour in education of engineers has generally been welcomed by students and teachers owing to the reduction of their work-load and by the Government to reduce the cost of producing engineers.

Another unintended fallout occurred owing to the emergence of the computer-aided design in recent past. Prior to about 1991, design calculations had to be done meticulously by hand-calculator, and designs naturally tended to be simple, symmetric, and regular in plan and elevation. After 1991, computer analyses were increasingly used and the practice of vetting design calculations by independent engineers was gradually done away with. This change promoted the construction of highly irregular (in both plan and elevation) buildings that were far more prone to progressive collapse than the simple buildings built much earlier. Computers also allowed greater optimization resulting in lesser available overstrength. This is another reason why the buildings built within the past 10 years suffered greater damage compared to buildings built much earlier during the Kutch Earthquake of 26th January 2001. After the emergence of the computer in education, the feel of the design process and behavior of structures has declined. Therefore, approximate methods of analyses also need to be reintroduced in the curriculum.

PBE uses non-linear analyses for evaluation of structural designs. It requires far greater quality control in selection of structural materials and in construction. Both the lower and upper bound strengths of structural materials need to be known, and for economical design these strengths need to be in a narrow range. It requires selection of suitable architectural configuration so that the structural engineer can economically and reliably design a ductile collapse mechanism. It requires use of capacity design method so that a ductile collapse mechanism with stable hysteresis is formed and possible brittle collapse mechanisms are avoided. It requires a far greater knowledge about material properties and member component behavior so that the non-linear analytical model can be made. If these conditions are not met, PBE analyses are unlikely to result in safer structures. PBE, thus, requires a much tighter interaction between architects, structural designers, structural analysts, contractors and supervisors. For this, these specialists need to know each other's role to a much greater extent. Therefore, education of civil engineers must have some courses from architecture, more practical training in construction aspects, involve drafting of structural drawings, more design courses, besides the needed elements of earthquake engineering in the form of courses in structural dynamics, soil dynamics and engineering seismology.

Where is the space for these courses in a Bachelors degree curriculum? One of the possible solutions is to increase the duration of the bachelor's degree in civil engineering so that needed courses for PBE can be included in the curriculum. This will result in different durations for the bachelor's degree in different engineering disciplines. But, the duration of Bachelor degree in Architecture, in Arts, in Science, in Medicine, is already different from the duration in Engineering. The uniform duration and treatment in degree programs of different engineering disciplines is a consequence of their emergence from military engineering and growth in same institutions. But, this uniform duration does not guarantee equal employment prospects and equal emoluments in a market economy. So why not allow different engineering disciplines to devise their curricula as per their unique needs? If this idea is accepted in principle, then it may still be possible to devise a four-year bachelor's degree program in civil engineering at IIT Roorkee with the needed ingredients for supporting PBE! This is at present difficult because of a development that took place around 1965 that unfortunately resulted in uniform policies for all engineering disciplines.

In Roorkee, around 1965, the duration of Bachelors degree programs in all engineering disciplines was increased from three years to four years. A common first year curriculum and common courses in physics, chemistry, mathematics, humanities and in some engineering subjects were compulsorily imposed in all branches of engineering. This was based on the premise that "science" forms the foundation of "engineering" and "humanities" is required to inculcate human values among engineers. Engineering teachers opposed the introduction of these common subjects, because their students were sufficiently groomed in them even before they entered the Bachelors program for engineers, and their proficiency in these subjects was thoroughly tested by the very tough entrance examination in vogue in Roorkee. Each branch of engineering may still require further grooming in these subjects, but this grooming would be different for each branch, and not common for all branches. This decision had the following adverse consequences.

1. By imposing these courses compulsorily on all engineering disciplines, the authority and the responsibility of the engineering department, offering the degree, was irretrievably diluted.

   At present, in IIT Roorkee, 45% of the B.Tech. curricula in all engineering disciplines consist of such compulsory and common courses (IITR, 2002). If civil engineers prove unsuitable as field engineers or do not get the needed elements of earthquake engineering in their education, then who is to blame and who has the authority and the responsibility to fix the curriculum? Since these imposed courses are compulsory and common, the civil engineering department cannot even touch the contents of these common courses. New courses cannot be added without removing others, as the curriculum is already sufficiently loaded. The contents of existing courses cannot be increased because the existing contents are already heavy. All that can be done by the civil engineering department is to substitute one essential departmental course by another.

2. Because these imposed courses were common and compulsory for all engineering disciplines, they became sufficiently general and abstract, with the result that these courses became rather irrelevant for all engineering disciplines.

   Even the engineering courses that were imposed on all branches suffered this fate. For example, civil engineering department at IIT Roorkee offers a common course in Engineering Graphics; and this course has been rendered sufficiently abstract (because it is offered to all branches) that it is rather irrelevant even for Civil Engineers. The course, Architectural Graphics that runs in the Architecture Department only would perhaps be more suitable for civil engineers also. In the common Physics course, every engineering student learns about Optics and Quantum mechanics. These topics do not provide the required foundation for civil engineers and, therefore, is not needed for education of civil engineers.

At present, IIT Roorkee has common courses in English, Economics, Management, Chemistry, Physics I and II, Bio-technology, Electrical Science, Electronics, Computer Systems and Programming, Engineering Graphics I and II, Mathematics I-IV, Manufacturing Processes, etc. These can be replaced by custom-made courses according to the unique needs of civil engineering and some of them can be eliminated to provide the necessary space for introducing the needed elements of earthquake engineering and for introducing PBE.

CONCLUSIONS

The present seismic standards in India promote the construction of seismically most vulnerable constructions in highly seismic areas of the country. This dubious intent has arisen owing to the need to ensure seismically "safe" housing to the people of India at a cost they can afford. Even earthquake disasters have failed to weaken this intent, because after every earthquake, the government desires to get the affected people rehabilitated in seismically "safe" housing at the minimum possible cost to itself. Unfortunately, this intent has resulted in lowering of seismic standards in India to levels much below that of developed countries and a false sense of security. If Type A non-engineered constructions are touted as adequately safe in Zone V, then Type B and Type C structures must be even safer; and, India appears as a seismically very safe place. That is why lessons learned from past earthquake disasters are yet to be adequately reflected in Indian seismic codes. Therefore, the current seismic standards of India pose a serious obstacle to the emergence of PBE in India, and that is why the author repeatedly dwelt on this theme in this paper. Better seismic standards are urgently needed in the new global economic setup and a working draft can be easily prepared by learning from ATC and FEMA documents developed in USA. This draft can then be widely disseminated, debated and improved upon by using the Internet.

United Nations has produced a global seismic hazard map under its Global Seismic Hazard Assessment Program (GSHAP) (UNIDNDR, 1999). The GSHAP map shows PGA values that have a 10-percent probability of being exceeded in 50 years. This map and/or the seismic zoning map, given in IS 1893-2002, can be used to specify the Design Earthquake levels for sites in India. To obtain design spectra corresponding to different site soil conditions, the amplification factors, found in ATC-40 and FEMA draft codes, can be used, until sufficient strong motion data is available in India for accomplishing this task independently. Maximum Earthquake and Serviceability Earthquake levels can be defined as per ATC-40, until contour maps showing the short-period and 1-second period spectral accelerations for India are developed.

Considerable effort will still be required to translate the modeling guidelines and evaluation criteria available in PBE draft codes (ATC, 1996; FEMA 1997b, 2000) for use in India, because the system of units, testing procedures and construction practices in India are different from those in USA.

Civil engineering education needs to be reformed to include the needed elements of earthquake engineering to provide a base for PBE. Fortunately, this aspect is already in focus of the NPEEE. This paper expresses an opinion on the direction of the needed reforms.

Seismic vulnerabilities in India have been increasing rapidly since 1991 due to increased construction activity owing to economic resurgence in the country after it embraced the global market economic model. Continued economic growth is likely to result in shorter design life of existing seismically vulnerable buildings, and provide the needed funds for their replacement by seismically more robust buildings. Therefore, in spite of the present shortcomings, the future of Performance Based Engineering in India is bright!

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