A Review on the Seismic Vulnerability of Oil and Gas Pipelines in Guwahati City

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Abstract: Crude oil in the northeastern state of Assam was discovered in the late 19th century in the eastern reaches of the state. With passage of time the oil, natural gas and petroleum products were transported from Assam to various parts of the country via pipelines. The pipelines traversing through the length of the state pass over or are located close to several tectonically active faults. Some of the noteworthy faults are Oldham fault, Kopili fault and Dhubri fault. These faults have been the sources of several past damaging earthquakes (EQs) such as the 1897 Assam EQ (M_W=8.1), 1869 Cachar EQ (M_W=7.5), 1943 Assam EQ (Ms=7.2) and 1930 Dhubri EQ (Ms=7.1) respectively. The 1157 km long automated trunk pipeline used to carry products from Oil India Limited (OIL) and Oil and Natural Gas Corporation (ONGC) pass directly over the Kopili fault. The upcoming Barauni-Guwahati gas pipeline by GAIL will cross the Dhubri fault and will also be located very close to the Oldham fault. Thus the pipelines are at risk of being subjected to high intensity of shaking from future earthquakes. Further, since the time of laying of the pipelines no major or great earthquakes have occurred in Assam. Hence, the seismic vulnerability of the pipelines remains unknown. This review study is an attempt to understand the seismic vulnerability of the pipelines located in the vicinity of the Guwahati city and in case of failure its impact on the inhabitants of the city.

Keywords: Earthquake, Seismic vulnerability, Pipelines.

1. Introduction

Fossil fuels have always played an important role in shaping the modern face of a nation. India too has leapt forward in the race of globalization by making use of the rich oil reserves in various parts of the country, including those found in the state of Assam. Crude oil was first discovered under the British rule in the year 1866 in Margherita, Assam [1]. Since then, crude oil reserves have been discovered in several places in the eastern reaches of the state. This important natural reserve is transported via pipelines to various parts on the country since its commencement in the year 1962 [2]. These pipelines which are often referred to as “lifelines” carry crude oil, petroleum products and natural gas across the states of Assam, West Bengal and Bihar and in this process transverse across several active faults. Baro and Kumar [3] have identified several of these active tectonic faults lying across the length and breadth of Assam. Most of these faults, located in the vicinity of Assam, have generated damaging earthquakes (EQs) in the past. Some of the past EQs include; 1869 Cachar EQ (M_W - 7.5), 1897 Assam EQ (M_W - 8.1), 1923 Meghalaya EQ (M_S - 7.1), 1930 Dhubri EQ (M_S - 7.1) and 1943 Assam EQ (M_S - 7.2). Baro and Kumar [4] highlight that the source faults of these EQs are Kopili fault, Oldham fault, Dauki fault, Dhubri fault and Kopili fault respectively. The damages from these EQs were clearly evident within the city of Guwahati (26.14^{o}N, 91.73^{o}E). Oldham [5] observed that during the 1869 Cachar EQ several important government and public buildings in Guwahati city had suffered damages. Compared to 1869 Cachar EQ, the intensity of shaking from the 1897 Assam EQ was much larger and consequently the damages were also more. Liquefaction and ground fissures were observed at several locations within Guwahati city during 1897 EQ [6]. During 1923 Meghalaya EQ, though the source fault was located at the southern boundary of the neighbouring state of Meghalaya, damages were reported at distant locations of Borjuli and Sivagasar in Assam [7]. These places are located further north of the existing Naharkatiya-Barauni Crude Oil Pipeline. During the 1930 Dhubri EQ, shaking was felt from Dhubri in the west, to Guwahati city in the central part of Assam. As per Gee [8], an intensity of VII (on Modified Mercalli Intensity scale) was felt across the Guwahati city. Information related to damages from the 1943 Assam EQ are very limited. As per CNDM [7], ground fissures and damaged buildings were reported from several places across Assam. Collectively based on the discussion above, it can be observed that Assam has a long history of major to great EQs occurring at frequent intervals. Further, occurrences of above EQs led to ground fissures and liquefaction. Considering the oil reserve of Assam and the infrastructure available in practise to transfer the oil/ gas to other parts of the country as highlighted earlier, in case of ground fissures and liquefaction occur during future EQs, these can even lead to damages in pipelines.

It is interesting to note that all of these damaging EQs had occurred prior to the laying of the crude oil, product and natural gas pipelines across Assam i.e. before 1962. Further, it has to be highlighted here that after 1962 no major to great EQs have occurred along these faults. Hence, it is difficult to ascertain how sustainable will be these pipelines if EQs of characteristics witnessed in the past occur during present times. Speculations are rampant that the Oldham fault which has already generated a great EQ, and the Kopili fault which has generated two major EQs are capable of doing the same in the near future [9,10]. Interestingly enough the Naharkatiya-Noonmati segment of the Naharkatiya-Barauni Crude Oil Pipeline passes transversely over the Kopili fault. The remaining Noonmati-Baruani segment is laid across the Dhubri fault, which was the source fault for the 1930 Dhubri EQ. The proposed Barauni-Guwahati gas pipeline will also be laid across the Dhubri fault and in close proximity to the Oldham fault. The product pipeline from Numaligarh to Siliguri also passes over the Kopili fault, Dhubri fault and is located close to the Oldham fault.

Since these pipelines are essential for the economic sustainability of the region it is very important that the pipelines withstand the shaking from EQs. Further, since the Naharkatiya-Barauni Crude Oil Pipeline and Numaligarh-Siliguri product pipeline passes through the highly populated city of Guwahati, it becomes crucial to know about the seismic vulnerability of the pipelines. This review study is aimed towards identifying the seismic vulnerability of pipelines, highlighting the state of the art methods available to address the same and in case of failure its impact on the inhabitants of Guwahati city.

2. Tectonic setting of Assam

The Assam valley is a result of deposition of several tonnes of sediment brought in by the rivers Brahmaputra and Barak [3]. As per Angelier and Baruah [11], the overburden thickness of the sediment reaches below 5 km from the ground surface. Below this heavy deposit of sediments, lie several active tectonic faults which have been the source faults of past EQs. One of the faults closest to Guwahati city is the Oldham fault, which is located to the west of the city [12].The Oldham fault which is a 110km long fault dipping 57° to the south was responsible for the 1897 Assam EQ (M_W - 8.1) [13]. As per Bilham and England [13] the shaking from the 1897 Assam EQ was so high that it generated another fault called Chedrang fault (CF) next to the Oldham fault. To the east of the Oldham fault is the Kopili fault which is 300–400 km long and 50 km wide. The Kopili fault is a northeast dipping strike slip fault which was the source fault for two major EQs 1869 Cachar EQ (M_W - 7.5) and 1943 Assam EQ (M_S - 7.2). Further east of the Kopili fault are the Churachandpur–Mao fault (CMF) and Kabaw fault. According to Wanget al. [14], the CMF is a 170 km-long strike–slip fault which could possibly produce an EQ of $M_W = 7.6$ in the future. Wang et al. [14] also speculate that the Kabaw fault, which is a strike–slip fault with a 45° dip, has the potential to produce an EQ of $M_W = 8.4$ in the future. Towards north-west of the (CMF) and Kabaw fault is the Dauki fault separating the Shillong Plateau from the plains of Bangladesh. The Dauki Fault is a south dipping normal fault with a strike–slip component trending from east to west of the Shillong Plateau [15]. The Dauki fault was the source of the 1923 Meghalaya EQ. A northwest extension of the Dauki fault is the Dapsi thrust (DT). Further west of the Dapsi thrust, the western boundary of Assam is marked geologically by the north-south trending Dhubri fault which was the source of the 1930 Dhubri EQ (M_S - 7.1). North of Dhubri fault and the Assam Valley, lying beneath the foothills of the Himalaya, is the east-west-trending Main Boundary Thrust (MBT). The MBT runs parallel along the entire length of Assam. North of MBT is the Main Central Thrust (MCT) which also runs along the entire length of the north-eastern part of the Himalayas. Though the portion of the MBT and MCT beyond north-eastern India have generated several EQs, the segments of both the faults within northeast India have not generated any EQs in recent times. Mittal et al. [16] have called this segment of the faults between the epicentres of the 1950 Assam EQ and the 1934 Bihar-Nepal EQ as the "Northeast Seismic Gap". Mittal et al. [16] speculate that this seismic gap has the potential to produce an EQ of $M_W = 8.5$ in the near future. The above mentioned faults are some of the potential sources for future damaging EQs which could impact the stability of the pipelines. Apart from these major sources there are several other faults located in the vicinity of Guwahati city. Baro and Kumar [3] had identified 72 faults located within a seismotectonic region of 500km for estimating the seismic hazard potential of the

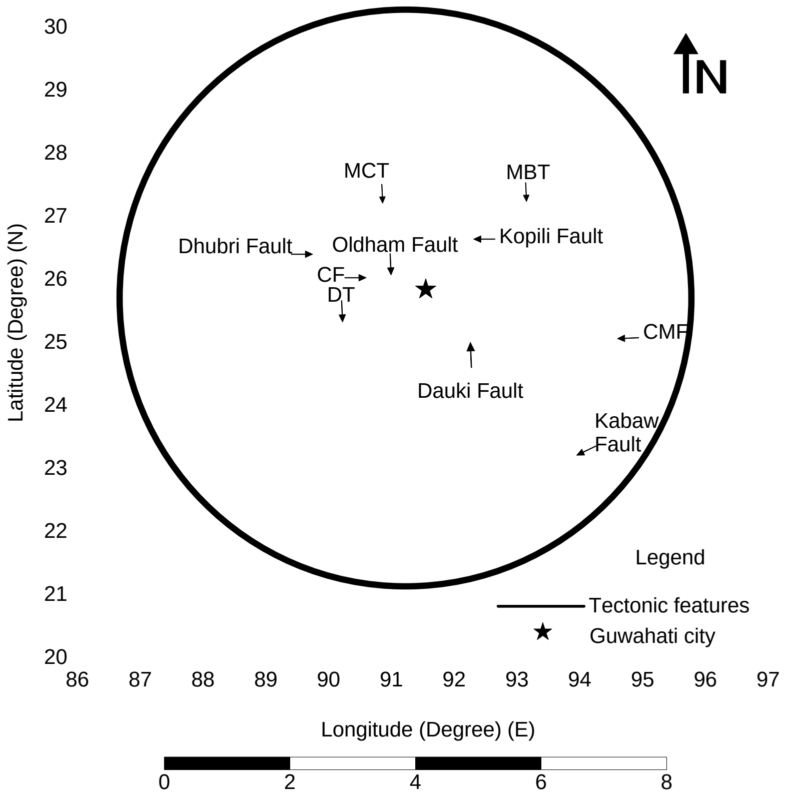

Fig. 1. Source map showing all the faults located within 500km radius from Guwahati city (CF- the Chedrang fault, CMF- Churachandpur–Mao fault and DT- Dapsi thrust) (modified after [12])

Shillong Plateau. A similar approach is adopted in this study to identify the faults which could possibly affect the seismic vulnerability of the pipelines located near Guwahati city (see Fig. 1).

3. Local soil condition of Guwahati city

Guwahati is a major city in Northeast India, sometimes even referred to as the "Gateway of Northeast India". Guwahati city was conceived in the flood plains of the Brahmaputra valley. Located to the south of the river Brahmaputra and north of the Shillong Plateau, the city currently houses 9.57 lakh inhabitants. Geologically the city is composed of hills and valleys. Granitic rocks dating back to the Precambrian era form the hills and Quaternary sediments fill up the valleys [17]. SPT test conducted by Raghukanth and Das [17] revealed that the sediment deposits available in the city are composed of layers of sand, silt and clay. The SPT-N values were found to be very low at several locations across Guwahati city.

In another study, Nath and Thingbaijam [18] used data from vertical electrical-resistivity sounding (VES) and 30 boreholes to obtain the basement topography of Guwahati city. This data revealed that the basement is composed of hard granite rock. Nath and Thingbaijam [18] also collected N value from 200 boreholes dug at various locations around Guwahati city. The SPT-N values were then used to obtain the average shear wave velocity profile of the city. It was found that the flood plain sediments of the Guwahati city belong to site class D, with a shear wave velocity V_s^{30} ranging from 180-360m/s. The borehole data also helped deduce the ground water level, which was found to be located at very shallow depths of 1.5m. Taking into account the factors of high level of seismicity, shallow water table and soil type of site class D, it can be expected that the city might be vulnerable to liquefaction.

To ascertain the liquefaction potential of Guwahati city Ayothiraman et al. [19] performed detailed microzonation study. Ayothiraman et al. [19] collected data from 100 boreholes dug in an area of 9km by 7km within the city. The SPT-N values were obtained at 1.5m intervals up to a depth of 15m. The SPT tests revealed that most sites across Guwahati city are susceptible to liquefaction failure. Ayothiraman et al. [19] then considered a scenario similar to 1897 Assam EQ, with the source located at an epicentral distance of 50km and a PGA value of 0.36g. It was found that the factor of safety for most of the boreholes was less than 1. This implied that most of the locations within Guwahati city will undergo failure due to liquefaction in case an EQ of M_W=8.1. Work by Khan and Kumar [20] based on larger set of borehole information and four different seismic scenarios also highlighted that Guwahati soil has high liquefaction potential and provided guidelines for the improvement of such sites in order to avoid liquefaction. Thus from recent studies it can be concluded that the liquefaction potential of Guwahati city is high.

The results obtained by recent studies on the liquefaction potential of Guwahati city are in sync with those reported during the 1897 Assam EQ. As per Bilham and England [13], the source of the 1897 Assam EQ is the Oldham fault which is located adjacent to Guwahati city. The closeness of the fault to the city left its devastating mark in the form of structural damage as well as geotechnical evidences. The damages that occurred during this EQ were reported in details by Oldham [21]. Oldham's [21] report revealed the occurrence of liquefaction as it was observed that the abutments of the bridge on Grand trunk road had moved forward while one of the piers was tilted over. In addition to liquefaction observed during the 1897 Assam EQ, ground fissures were observed at several locations. In Guwahati city all along the banks of river Brahmaputra large fissures were observed and the adjacent ground subsided. Several sand vents were created at various locations across the state. Ground fissures were also observed at several locations across the Guwahati-Shillong road [21]. As per Bilham [6] the shaking from the EQ was so severe that it generated landslides along the Guwahati–Shillong road.

From the recent studies and past reports it can be ascertained that the local soil of Guwahati city is susceptible to liquefaction, ground fissures and landslide. Along with these factors wave propagation and faulting are some of the factors which cause damages to pipelines. Damage to pipelines across the globe due to above mentioned factors is discussed in the next section.

4. Reports of damages to pipelines during past EQs

Accounts of pipelines across the globe that have undergone damages due to previous EQs are discussed below.

4.1 1971 San Fernando EQ (Mw-6.6)

Ground fissures and lateral spreading due to liquefaction can be a major cause of damage to pipelines as it was witnessed during the 1971 San Fernando EQ. Buried ductile steel pipes were reportedly damaged due to faulting and lateral spreading [22]. An old oxy-acetylene welded pipeline was reported to be most affected. Landslides and local compaction of the ground also contributed towards the buckling and rupture of buried pipelines [23].

4.2 1985 Michoacan EQ (Mw-7.6)

It is interesting to note that during the 1985 Michoacan EQ there were no reports of liquefaction, landslides or faulting. However there were reports of damages to water pipelines. Ayala and O'Rourke M. [24] deduced that the damage in the pipelines were mostly due to surface wave propagation. Ayala and O'Rourke M. [24] observed that most damages to pipelines had occurred due to amplification of surface wave in the lake zone of the Valley of Mexico which consisted of 30 to 70m deep clay deposits [25]. In addition the lake zone had also undergone settlement which further contributed to the damage in the pipelines.

4.3 1989 Loma Prieta EQ (Mw-6.9)

The pipelines located in Loma Prieta underwent damages due to liquefaction and ground fissures. During the 1989 Loma Prieta EQ mostly water supply pipelines were damaged and among gas pipelines the worst affected were the gas mains and service lines of Pacific Gas and Electric Company [26].

4.4 1994 Northridge EQ (Mw-6.7)

During the 1994 Northridge EQ a total of 1400 pipeline breakages were reported across the San Fernando Valley [26]. Most of these breakages were reported in areas of high liquefaction potential. The breakage in the gas pipelines led to fire breakouts at several locations in the San Fernando Valley [22].

4.5 1999 Izmit EQ (Mw-7.6)

During the 1999 Izmit EQ the highest damage was reported from the water supply distribution system in Adapazari. Most of these damages were due to crossing of pipelines over tectonic faults. In one case a steel pipe passing over a right lateral strike slip fault was damaged. Again similar damage was observed in a pipeline crossing the North Anatolian fault [27].

4.6 1999 Chi-Chi EQ (Mw-7.6)

During the same year another EQ of similar magnitude occurred in Taiwan, famously known as the Chi-Chi EQ. During the 1999 Chi-Chi EQ several buried gas pipelines were bent as a result of ground deformation due to the movement at a reverse fault about 10 km south of Taichung [27].

From the above discussion it is evident that pipelines are vulnerable to the aftereffects of an EQ. It can be observed that most damages in the pipelines have occurred due to local site effects and/or crossing over active faults. It has been mentioned earlier that the pipelines located in Assam have not yet experienced any major to great EQs. Thus the pipelines have also not undergone any damages related to local site effects and faulting. However it has been established that the local soil of Guwahati city is vulnerable to local site effects and thus the pipelines crossing through the city are equally at risk.

5. State of the art seismic vulnerability studies for pipelines

The above discussion clearly highlights the fact that pipelines are vulnerable to seismic hazards. Hence to evaluate the seismic vulnerability of pipelines it is essential to estimate the seismic hazard potential of the soil within which the pipeline is laid. It has been mentioned earlier that the local soil within Guwahati is susceptible to liquefaction. As per Honegger and Wijewickreme[28], liquefaction induced lateral spreads tend to cause more damage to pipelines than liquefaction itself.Past studies conclude that lateral spread is generally observed at places close to river banks. Damage reports from 1897 Assam EQ indicate the occurrence of lateral spreading along the banks of Brahmaputra [17]. The oil and gas pipelines considered in this study crosses the Brahmaputra near Noonmati from its southern to northern bank and then continue their journey west. Thus, taking into account past studies and damage reports, it could be said that the segment of pipeline close to the river crossing at Noonmati, may be susceptible to damage from lateral spreading. It has to be mentioned here that although studies have been performed to estimate the liquefaction potential, very limited to no in-depth study on the inducedlateral spreading in Guwahati city has been performed.

In order to understand the seismic vulnerability of pipelines passing through Guwahati city, it is essential to estimate the EQ induced lateral spreading potential of the Brahmaputra river bank. Computation oflateral spreading of soils can be performed using empirical as well as mechanistic approaches. Empirical approaches provide regional assessment of lateral ground deformation whereas mechanistic approaches are more site specific. As per Honegger and Wijewickreme[28] for wide spread structures such as pipelines, regional assessment based on empirical approach is more suitable. One such study was performed by Youd and Perkins [29] where the Liquefaction Severity Index (LSI) was used to estimate the maximum horizontal ground displacement at a liquefiable site. The empirical correlation was restricted to estimation of LSI for lateral spread occurring along gently-sloping sediments deposited during late Holocene period. The LSI was expressed in terms of EQ magnitude and log of distance between the source and site as shown below:

$$\log LSI = -3.49 - 1.86 \log R + 0.98 M_w \quad (1)$$

where, LSI is maximum expected permanent horizontal displacement; R is shortest horizontal distance measured from the source to the site; and M_W is moment magnitude.

In another study, Bartlett and Youd [30] highlighted the limitations of [29] by stating that the previous study did not take into consideration site specific conditions. Further, taking seismological, topographical and geological data from Japanese and US case histories into account, and using Multiple Linear Regression (MLR), Bartlett and Youd [30], developed two empirical correlations. It was observed that induced lateral spread can occur along a free face of a river channel as well as along gentle slopes without a free face. Thus, two empirical correlations were developed as shown below:

MLR model for free-face conditions

$$\log(D_H) = -16.366 + 1.178M - 0.927 \log R - 0.013R + 0.657 \log W + 0.348 \log T_{15} + 4.527 \log(100 - F_{15}) - 0.922 D50_{15} \quad (2)$$

where,

$$W = \frac{100H}{L} \quad (3)$$

where, L is the horizontal distance from the channel; H is the depth of channel

MLR model for gently sloping ground conditions

$$\log(D_H) = -15.787 + 1.178M - 0.927 \log R - 0.013R + 0.429 \log S + 0.348 \log T_{15} + 4.527 \log(100 - F_{15}) - 0.922 D50_{15} \quad (4)$$

where, D_H is the estimated lateral ground displacement; M is the moment magnitude; R is the distance to the nearest fault rupture in kilometres; S is ground slope variable; T_{15} thickness of liquefied layer; F_{15} is average fines content; $D50_{15}$ is mean grain size.

In another study done by Youd et al. [31], it was observed that the equations given by Bartlett and Youd [30] had certain limitations. Youd et al. [31] using MLR model proposed a revision stating that the previous equations estimated erroneous values of lateral displacements for the 1983 Nihonkai-Chubu EQ (M_W-7.8). It was also found that Bartlett and Youd [30] had developed the equations based on data from sites where free lateral displacement was hindered by the boundary effects. Youd et al. [31] also incorporated data from additional sites to the revised equations which are shown below:

MLR model for free-face conditions

$$\log D_H = -16.713 + 1.532M - 1.406\,logR^* - 0.012R + 0.592\log W + 0.540\,logT_{15} + 3.413\log(100 - F_{15}) - 0.795\log(D50_{15} + 0.1mm) \quad (5)$$

MLR model for gently sloping ground conditions

$$\log D_H = -16.213 + 1.532M - 1.406\,logR^* - 0.012R + 0.338\,log\,S + 0.540\,logT_{15} + 3.413\log(100 - F_{15}) - 0.795\log(D50_{15} + 0.1mm) \quad (6)$$

where,

$$R^* = R + R_0 \quad (7)$$

$$R_0 = 10^{(0.89M - 5.64)} \quad (8)$$

where, D_H is the estimated lateral ground displacement, in meters; M is the moment magnitude of the EQ; R is the nearest horizontal or map distance from the site to the seismic energy source, in kilometres; T_{15} is the cumulative thickness of saturated granular layers with corrected blow counts, (N1)60, less than 15, in meters; F_{15} is the average fines content (fraction of sediment sample passing a No. 200 sieve) for granular materials included within T_{15}, in percent; $D50_{15}$ is the average mean grain size for granular materials within T_{15}, in millimetres; S is the ground slope, in percent, and W is the free-face ratio defined as the height.

In the future, the above mentioned equations can be used to estimate the lateral ground deformation potential of areas close to Brahmaputra river bank where the pipelines are located.

6. Details of pipelines passing through Guwahati city

The major pipelines carrying crude oil and petroleum products pass through Noonmati refinery in Guwahati city which acts as a refinery and major pumping station. One such pipeline is the Guwahti-Siliguri pipeline segment which carries petroleum products from Noonmati refinery in Guwahati to Siliguri in West Bengal. This pipeline is of length 435km with a diameter of 21.9cm and started operating in 1964. The total product carrying capacity of this pipeline is 818000 tonnes/yr. This pipeline is equipped with distribution points located at Betkuchi in Assam and Hashimara in West Bengal. This pipeline is owned by Indian Oil Corporation Limited (IOCL). The cost bared to lay this pipeline was 231600000 rupees [32].

Another crucial pipeline carrying crude oil from the oil wells of Digboi is the Naharkatiya-Noonmati pipeline. This pipeline is of length 401km, diameter 40.64cm and has been operational since 1960. This pipeline too traverses through Noonmati Refinery in Guwahati where the diameter changes from 40.64cm to 35.56 cm. Intermediate pumping stations located at Duliajan, Numaligarh, Jorhat and Sekoni in Assam helps pump the crude oil forward. This pipeline is owned by Oil India Limited

(OIL) and the construction and installation cost is estimated to be at 29,90,00,000 rupees [33].

The continuing segment of this pipeline is called the Noonmati-Barauni pipeline which carries the crude oil from Noonmati refinery in Guwahati city to Barauni in Bihar. This pipeline became operational from the year 1962. This pipeline is of length 756km and diameter 35.56cm. For this pipeline intermediate pumping stations are located at Bongaigaon in Assam, Madarihat in West Bengal and Domer in Jharkhand. This segment of the pipeline is also owned by Oil India Limited (OIL) [34].

Another upcoming pipeline project is the Barauni-Guwahati natural gas pipeline. This proposed pipeline will be owned by Gail (India) Limited. The pipeline is expected to be 729-km long and will cost approximately 11 billion rupees.

7. Effect of pipeline damage to Guwahati city from future EQs

From the above discussion, it is evident that Guwahati city is the main junction for the pipelines, carrying oil and gas from Assam to the rest of India. Further, it has already been discussed that pipelines are susceptible to damage from lateral spreading and active faults. This study has also highlights that local soil condition of Guwahati city is such that the occurrence of lateral spreads, ground fissures and sand vents is highly likely. Thus it is understandable that if in case of occurrence of an EQ similar to 1897 Assam EQ, damages to pipeline might be inevitable. In case of damage to pipelines carrying inflammable fluids, the highest threat would be fire hazard. Leakage or breakage of pipelines carrying oil and gas could lead to devastating effects. Reports from 1994 Northridge EQ highlight breaking out of 110 fires within the San Fernando Valley [34]. Some of the examples of fire breakouts during past EQs are 1906 San Francisco EQ (Mw-7.9), 1923 Kanto EQ(Mw-7.9), 1948 Fukui EQ (Mw-6.8), 1933 Long Beach EQ (Mw-6.4), 1971 San Fernando EQ (Mw-6.6) and 1989 Loma Prieta EQ (Mw-6.9) [35]. In addition, with increasing number of inhabitants and unplanned growth of Guwahati city, the risk of casualties and property damage increases. Currently Guwahati city has a population of 9.57 lakhs and only 5 fire stations in service. If multiple number of fire breakouts similar to 1994 Northridge EQ were to occur the damage to property and life would be unimaginable. It has to be highlighted here that the pipelines cross the river Brahmaputra at Guwahati. In case of rupture or leakage of pipeline, huge quantities of oil spill could occur into the river thus making the water unfit for consumption.

8. Conclusion

Guwahati city located in a zone of high seismicity is vulnerable to lateral spreading, ground fissures and occurrence of sand vents. These are some of the factors which possess threat to pipelines. Past studies have shown that pipelines lain over locations of liquefied soil, fissures and active faults have undergone damages. Some of the major crude oil and petroleum product pipelines of Assam pass through Guwahati city. Thus, taking into account past pipeline damage reports, local soil conditions and high seismicity level of the city, it can be assumed that the pipelines might undergo minor to significant damages. An in-depth vulnerability assessment study for the pipelines may be performed in the future.

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