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# FAILURE ANALYSIS OF BURIED GAS PIPELINES CROSSING SEISMIC FAULTS

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## Abstract

Research on buried gas pipelines (BGPs) has taken an important consideration due to their failures in recent earthquakes. In permanent ground deformation (PGD) hazards, seismic faults are considered as one of the major causes of BGPs failure due to accumulation of impermissible tensile strains. In current research, four steel pipes such as X-42, X-52, X-60, and X-70 grades crossing through strike-slip, normal and reverse seismic faults have been investigated. Firstly, failure of BGPs due to change in soil-pipe parameters have been analyzed. Later, effects of seismic fault parameters such as change in dip angle and angle between pipe and fault plane are evaluated. Additionally, effects due to changing pipe class levels are also examined. The results of current study reveal that BGPs can resist until earthquake moment magnitude of 7.0 but fails above this limit under the assumed geotechnical properties of current study. In addition, strike-slip fault can trigger early damage in BGPs than normal and reverse faults. In the last stage, an early warning system is proposed based on the current procedure.

**Key words:** Buried gas pipelines, seismic faults, normal fault, reverse fault, strike slip fault

## 1. Introduction

The economic strength of a country depends on their technological advancements and risk-based evaluation systems against any natural hazard such as landslide, droughts, hurricanes, flood, and earthquake [1]. Among all, earthquakes have great impact on the social disruption [2] and the main reason behind the severity of damages in BGPs [3]. Therefore, a reliable and quick procedure is required to investigate the BGPs after any devastating earthquake [4]. In recent years, various researchers have contributed well to improve this domain with their technical perspectives. For example, Lanzano et al. [5] described the pattern of damages in buried pipelines after seismic events. The output of Lanzano et al. [5] study has emphasized that BGPs are more vulnerable to geotechnical failures such as seismic fault crossing, liquefaction, and land sliding. The main cause of failure in BGPs is due to the development of seismic tensile strains [6]. Any minor interruption can cause energy stoppage and effect the daily life [7]. It can also be fatal if the interruption trigger fire or explosions [8]. Therefore, to avoid such losses, there should be a quick and emergency procedure needed to be adopted.

In current study, failure of BGPs due to seismic faults have been discussed in the form of flow chart given in Figure 1. The whole methodology is described in 3-step procedure. Firstly, problem statement is mentioned that emphasize on the importance of current study. Secondly, failure analysis procedure is described to assist the readers to understand clearly. In last step, failure assessment has been made to check which type of fault and grade of pipe cause early failure and the author has contributed more by developing an early warning system (EWS) for future researchers.

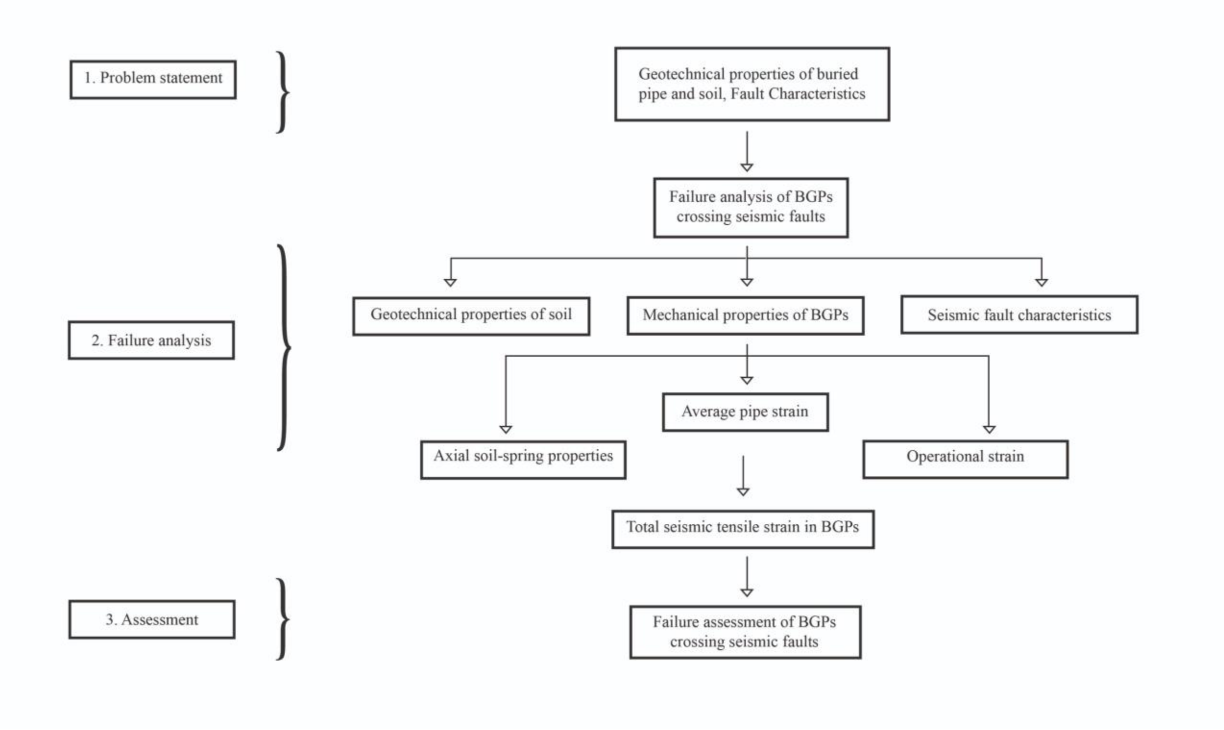

Figure 1. Flow procedure adopted in current study

## 2. Research and methodology

In current study, key methodology is already explained in Section 1. The input of current study is based on the examination of soil-pipe behavior. In geotechnical perspectives, nature of soil, humidity ratio, void properties and consolidations are important parameters. Likewise, burial depth, thickness of wall boundary, diameter and seismic importance factors are essential to consider for BGPs. The third and foremost element is the seismicity of the region where the assessment is planned to be assigned. After collecting this whole data, it is easy to evaluate the failure strain in BGPs crossing seismic faults. The theme of current study has received much attention in recent years. However, mostly the adopted procedure in past research was computational and time consuming. Therefore, the aim of current methodology is to make the whole procedure more simple, fast, and reliable. Four grades of pipes (X-42, X-52, X60 and X-70) with diameters (0.51m-0.81m), thicknesses (5-8 mm) and burial depths (1.2-1.5m) are used in current study. Effect of changing angle of internal friction of soil (25-40) have been examined.

Further, both seismic fault parameters and pipe class importance factors are also studied. After assessment, EWS system is developed to convert the whole procedure into digital form. In Figure 2. nature of BGPs crossing various seismic faults have been explained.

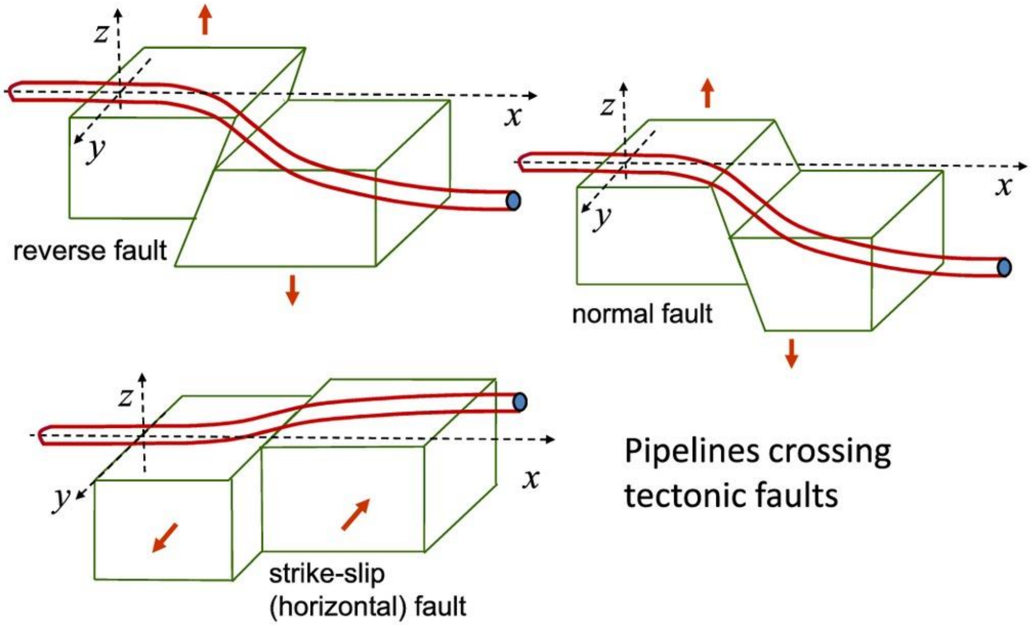

Figure 2. BGPs crossing seismic faults [9]

### 2.1. Design fault displacement

Firstly, expected fault displacement is essential to evaluate based on rigorous empirical based analysis. Many researchers have contributed well to this domain. In current study, widely used empirical equations developed by Copper and Smith [10] are preferred and are given below.

For strike slip fault displacement.

$$\log \delta_{sf} = -6.32 + 0.90M \quad (1)$$

For normal fault displacement.

$$\log \delta_{fn} = -4.45 + 0.63M \quad (2)$$

For reverse fault displacement.

$$\log \delta_{fr} = -0.74 + 0.08M \quad (3)$$

Then, component of fault displacement in both axial and transverse directions are evaluated.

Strike slip fault displacement in axial and transverse sides of BGPs are given in Equations 4-5.

$$\delta_{fax} = \delta_{fs}.\cos\beta \quad (4)$$

$$\delta_{ftr} = \delta_{fs}.\sin\beta \quad (5)$$

Normal slip fault displacement in axial and transverse sides of BGPs are given in Equations 6-7.

$$\delta_{fax} = \delta_{fn}\cos\psi\sin\beta \quad (6)$$

$$\delta_{ftr} = \delta_{fn}\cos\psi\cos\beta \quad (7)$$

Equations 6-7 are also used for the evaluation of reverse slip fault displacement in axial and transverse sides of BGPs but with negative signs.

Design fault displacement in axial and transverse sides of BGPs are computed by Equations 8-9.

$$\delta_{fax-design} = \delta_{fax}.I_p \tag{8}$$

$$\delta_{ftr-design} = \delta_{ftr}.I_p \tag{9}$$

## 2.2. Maximum seismic strain

The average pipe strain due to fault movement in axial direction is evaluated as.

$$\varepsilon_{av} = 2\left[\frac{\delta_{fax-design}}{2L_a} + \frac{1}{2}\left(\frac{\delta_{ftr-design}}{2L_a}\right)^2\right] \tag{10}$$

La = Effective unanchored length of the pipeline in the fault zone and is computed as.

$$L_a = \frac{E_i \varepsilon_y \pi D t}{t_u} \tag{11}$$

$t_u$ = Maximum axial soil force per unit length of pipe and is computed as.

$$t_u = \pi D c \alpha + \pi D H \bar{\gamma}\left(\frac{1+K_0}{2}\right)\tan\delta' \tag{12}$$

Maximum seismic strain is the sum of average strain accumulated due to fault movement and the operational strain due to pipe internal gas pressure and temperature difference.

$$\varepsilon_{seismic} = \varepsilon_{av} + \varepsilon_{op} \tag{13}$$

Operational strain is the sum of strains induced in BGPs due to due to pipe internal gas pressure and temperature differences and can be evaluated by using Ramberg Osgood's [11] Equation.

$$\varepsilon = \frac{\sigma}{E}\left[1 + \frac{n}{1+r}\left(\frac{\sigma}{\sigma_y}\right)^r\right] \tag{14}$$

In Equation (14). n and r are Ramberg Osgood's parameters and their values against each grade is given in Table 1.

Table 1. Ramberg Osgood's parameters

| **Pipe grade** | **X-42** | **X-52** | **X-60** | **X-70** |
|---|---|---|---|---|
| **Yield Stress (MPa)** | 310 | 358 | 413 | 517 |
| **n** | 15 | 9 | 10 | 5.5 |
| **r** | 32 | 10 | 12 | 16.6 |

## 3. Results and discussions

In current study, tensile strain failure of BCPs subjected to seismic faults is examined in detail. Geotechnical behavior of BCPs are observed due to change in soil- pipe parameters (SPPs) and fault plane patterns (FPPs).

### 3.1. Change in soil-pipe parameters

Soil-pipe parameters include angle of internal friction of soil, diameter, wall thickness, and burial depth of BGPs. The effect of changing these parameters have been examined in detail.

In current study, angle of an internal friction of soil is an important parameter that represents the ability of a soil to withstand shear stresses. According to USCS soil classification systems, friction angles between 25-40 shows low plastic to high plastic clayey soils. It is observed that as at small friction angle, computed strains in BGPs are also small. But as the angles become higher, tensile strains induced also becomes high. So, a direct relation is present between soil friction angle and tensile strain in the pipe. In current study, maximum strain is induced in X-42 grade steel pipe when crossed the strike-slip fault and vice versa. So, lower grade steel pipes fail first in strike-slip fault crossing when subjected to major earthquake with magnitudes (M) above 8.0.

Pipe diameter is also a critical parameter that permits to study the behavior of buried pipes in seismic regions. In current research, behavior of changing pipe diameters of different grade steel pipes crossing seismic faults has been examined. It has been observed that all grade pipes fail at earthquake magnitude 8.0 or above when subjected to strike-slip fault because computed tensile strains at M=8.0 is above than their allowable limits of 3%. But in the case of reverse fault crossing, all pipes operate safely even at M=8.0. Thus, in strike slip fault, changing pipe diameter does not provide safety at M= 8.0 or above but it operates safely in reverse fault. In normal faults, changing pipe diameter is critical as lower grade steel pipes fails first at M=8.0 or above.

Like pipe diameter, wall thickness of pipe is also an important parameter to study the behavior of buried pipes crossing different faults. In current study, as the values of wall thickness is minimized, the tensile strain induced in the pipes becomes high with the increase of earthquake magnitudes. Failure response is somewhat like previous parameters. X-42 pipe gains the highest tensile strain value when crossing to strike-slip fault.

Burial depth effect has been examined to check the behavior of pipes subjected to seismic fault crossings. It has been observed that at shallow depths, pipelines are more prone to damage due to increment of tensile strain values. Pipes fail at earthquake with M8.0 while crossing strike-slip fault but operates safely at reverse fault crossing even at M=8.0.

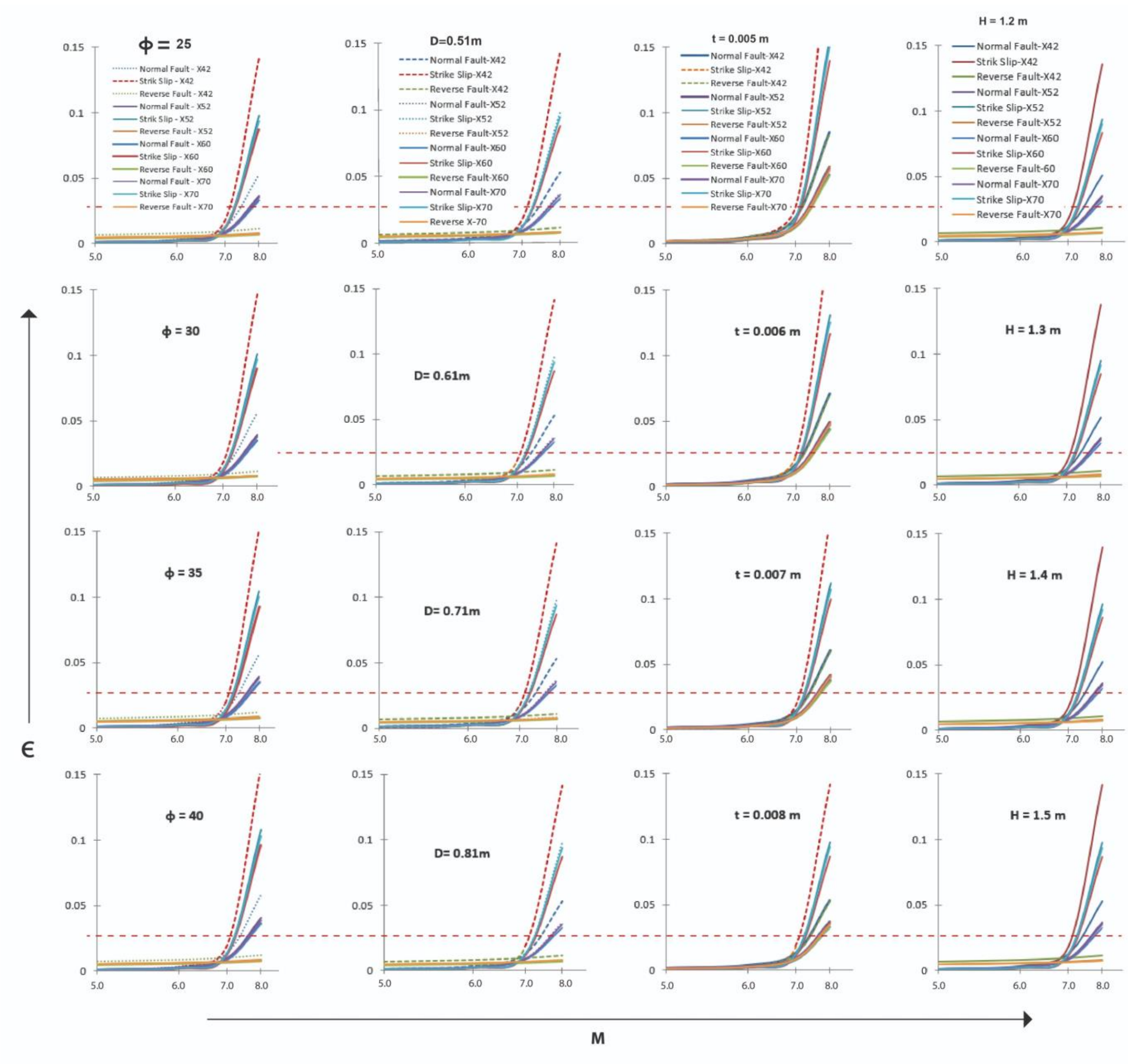

Figure 3. Effects due to changing soil-pipe parameters

### 3.2. Changing seismic fault parameters

In normal and reverse fault analysis, dip angle and angle between BGPs and fault plane are considered as one of the key factors for failure of BGPs during seismic events. Dip is the angle of moving plane with its horizontal surface and is denoted with symbol $\psi$. Further, the placement of pipe in such faults also accumulate strain that cause bending inside the pipes. Therefore, the angle between pipe and fault plane is symbolized with $\beta$ sign.

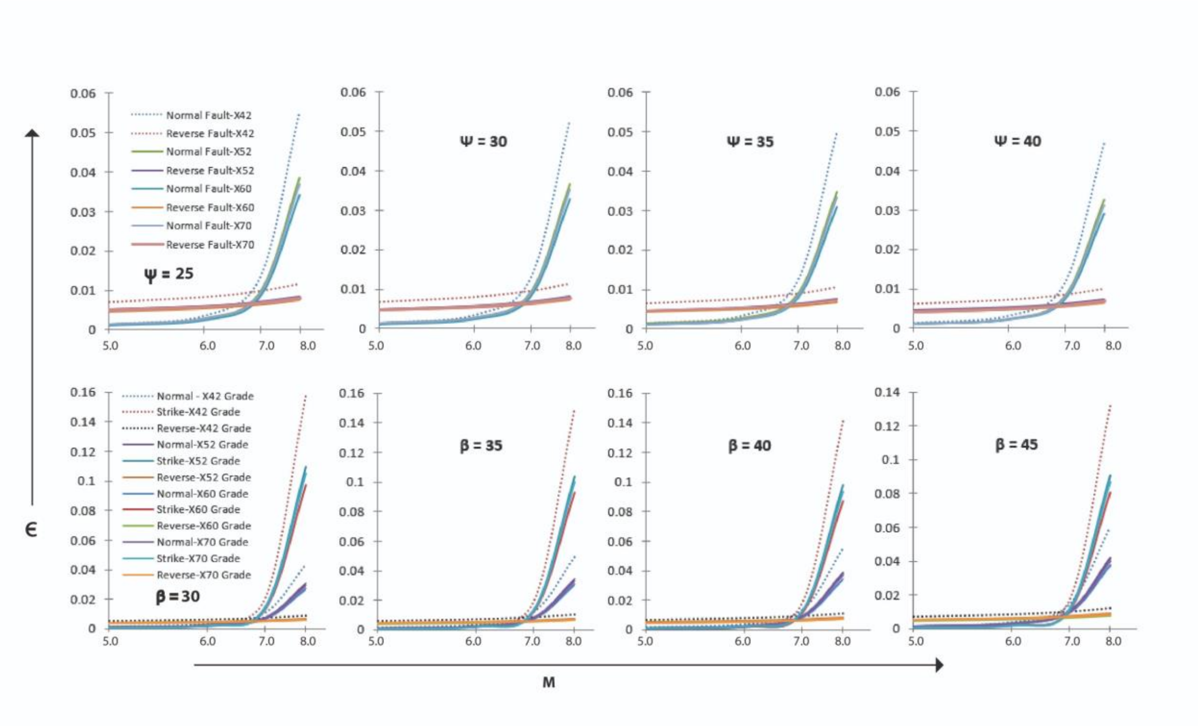

Figure 4. Effects of dip angle and angle between fault plane and BGPs

### 3.3. Changing pipe classes

According to Recommended Practices for Earthquake Resistant Design of Gas Pipelines developed by Japan Society of Civil Engineering [12], there are different pipe classes (PCs) importance factors to be considered for BGPs designing and analysis. For fault crossing, their recommended values vary from 1.0-2.3. It is seen in Figure 5. that lower the pipe class importance factor lowers the development of tensile strains in it. So, it is recommended to use lower pipe class importance factor if possible, to minimize the development of strain.

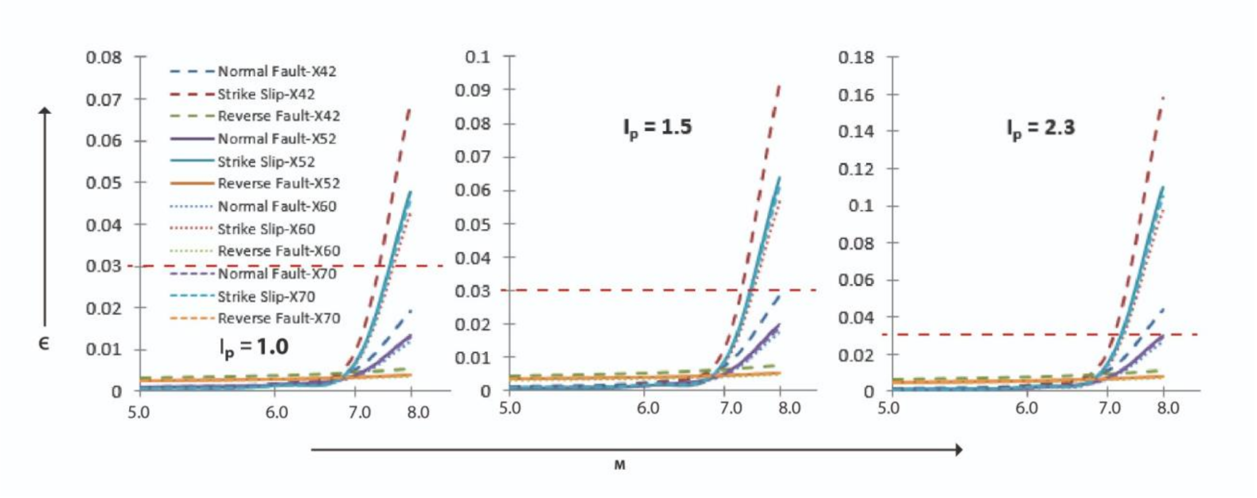

Figure 5. Effects of pipe classes on BGPs

## 4. Development of early warning system

The procedure adopted and explained before is converted to a monitoring and early warning system. The system is represented in Figure 6. It has four phases. First phase is observation point. In this stage, strain accumulated in BGPs due to seismic loading, internal gas pressure and temperature variations are observed. Further, nature of fault movement (NFM) and strength of earthquake based on strong motion (SGM) records are examined. The second phase is the data acquisition and processing unit that transfers the data to wireless communication system. Beidou satellite and 4G technology can be preferred to transfer the unreadable data to remote control receiving unit for display. The third phase is the analysis/display and management system. Display screen are used for exhibition of earthquake early warning (EW), BGPs strain induced, leakage and location required for inspection. The output data can be shared by text messages, email, or smart watches. The fourth and last phase is the alarm system. If any parameter exceeds the threshold limit value (in case of tensile strain limiting value is taken as 0.003), alarm and light color will demonstrate the emergency.

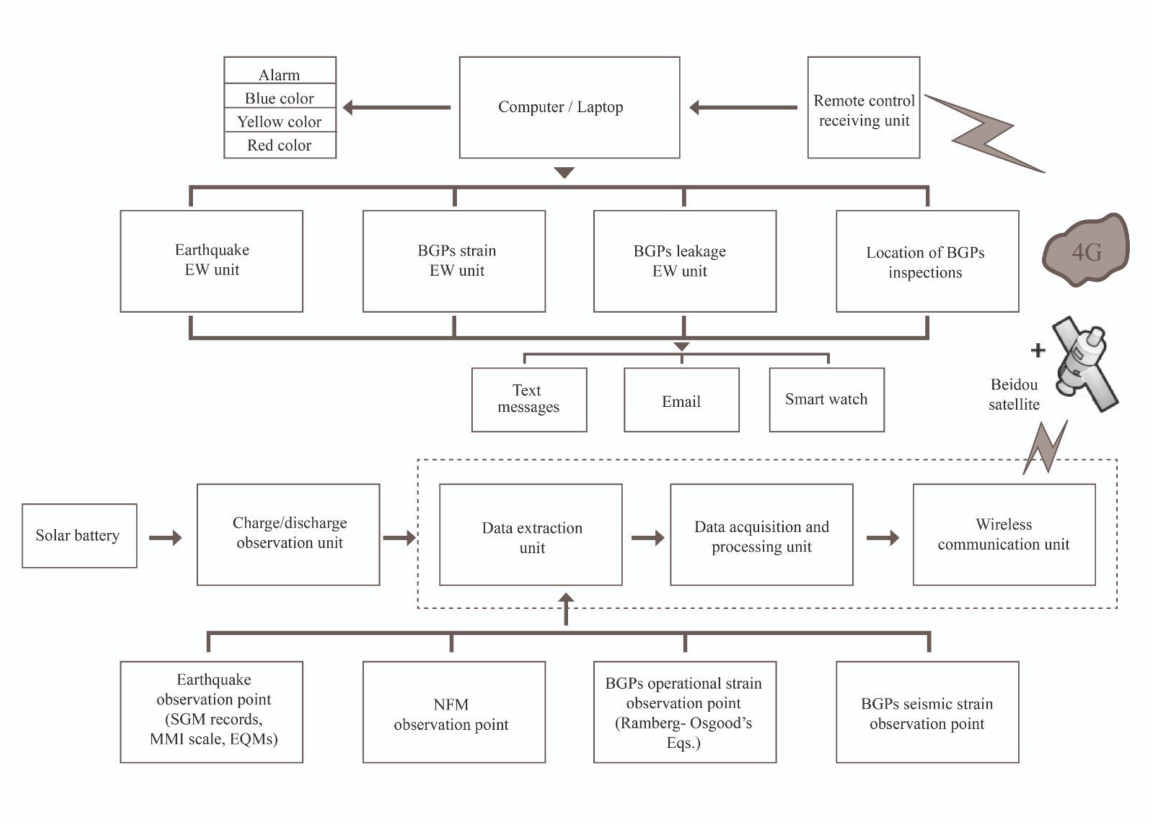

Figure 6. Development of EWS for safety of BGPs against seismic faults

## Conclusions

Current study is divided into two sections. In first phase, an anlytical based study is done to observe the preliminary performance of different grade BGPs subjected to three different seismic faults. In second section, a monitoring and an early warning system is developed. The results of current study reveal that SPPs are important for assessment of seismic behaviour of BGPs at regions with earthquake magnitudes (EQMs) ≤ 7.0. It has been seen that by increasing the values of φ, D, t and H for BGPs, the total tensile strain is increased. So, SPPs have directly proportional relationship. Further, all BGPs operate safely until EQMs 7.0 or lower but fail at 8.0 or above. It has also been seen that X-42 grade steel pipe is more prone to damage first than the other grades. Higher the grade of BGPs mean more safer side for the case of SPPs analysis. Further, It is obderved that for the highest seismic alert areas with EQMs > 7.0, FPPs and PCs can also play a significant role. For safe operation of BGPs, it is noted that the dip angle should be kept higher and angle between pipeline and fault plane should be small. In last section, an EWS is presented for BGPs that offers a new way to reduce the seismic damages. The developed approach can quickly control the safe operation of BGPs and shares the early warning data with concerned authorities.

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