A comparative study of different kinematics-based methods to predict the time of slope failure

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Abstract. Landslide forecasting is considered one of the key components of early warning systems. Predicting landslide failure at the slope-scale is a major scientific challenge, but on the other hand, it can mitigate the consequences of slope failures in terms of both human lives and economic losses. Therefore, landslide forecasting is a subject worthy of further research efforts due to its social implications. Landslide forecasting consists of the prediction of a slope failure in spatial and/or temporal terms. Temporal prediction can be performed at a regional/global scale or on a slope-scale. This paper focuses on the different methods for temporal prediction of landslides on a slope scale based on kinematic parameters such as displacement and its derivatives (velocity and acceleration). These kinematic parameters are directly related to the stability conditions of the moving mass. This paper accurately explains the correlation between the kinematics and the collapse time of a slope. Also, the present study systematically explains and compares the methods such as the empirical and semi-empirical methods for forecasting the failure time of slopes with their corresponding advantages and limitations. Finally, a detailed outline of the future technology and risks in this area are also introduced in this paper.

Keywords: Landslides, Forecasting, Kinematic Parameters, Empirical Method, Semi-Empirical Method

1. Introduction

Landslides are massive soil, rocks, and vegetation movements due to the instability of slopes created by both man-induced (deforestation, excavation, mining and quarrying, improper land use) as well as natural (weathered or sheared materials, heavy rain falls, earthquakes) activities [1]. They result from the failure of the materials which fall down the slope due to the force of gravity. The massive movements occur when the shear stress exceeds the shear strength of the material. Falling, toppling, sliding, spreading, or flowing may lead to the movement of the materials. In India, landslides occur primarily in the Himalayas of North India and the Western Ghats of South India. Kerala was affected by many landslides in all the rainy seasons and the most severe landslides occurred at Kavalappara and Puthumala of Wayanad district in the year 2019 and Pettimudi of Idukki district in the year 2020. These massive landslides crushed many settlements and buried small communities. It is
only rare that sudden slope failure happens without any prior signs. In most situations, cracks due to tension or shear may appear near the vulnerable area or mild displacement or deformation occurs to the structures situating near to the slope. It is relatively harder to find those signs or proceed to look at them for a long period in the case of minor or faster movements. Therefore, slope failures may occur suddenly without many indications [2]. Hence an effort is necessary to determine the indications of unstable slopes for the prediction of the time of failure.

Landslide forecasting involves predicting the collapse of a slope spatially or temporally. Spatial forecasting can be carried out by utilizing three maps such as hazard, risk, or susceptibility maps. Susceptibility mapping includes classification, area or volume estimation, and evaluation of the spatial distribution of existing and possible landslides in the area under consideration. Hazard maps are done by finding out the frequency (i.e. annual probability) of the landslides and risk maps help to assess the possible harm to components under risk [3].

The temporal prediction of landslides includes the determination of when the collapse of the soil mass occurs within a reasonable margin of error [4]. It is possible to make temporal predictions regionally, globally, or at slope scale and typically the adoption of the scale depends on the parameters tracked. Temporary prediction of slope magnitude landslides using slope dynamic parameters (positional movements and its derivatives (velocity and acceleration)) is considered to be a more reliable technique for predicting slope failure time [5].

Temporal prediction of landslides at slope scale employing kinematic parameters (displacements and their derivatives) of the slopes is considered to be a more reliable technique for predicting slope failure time [5]. The continuous landslides scenario is that only a small percentage of the world's landslides are properly monitored. Monitoring is often performed for short periods that do not contain the final pre-failure stages. Also, monitoring with a very low frequency does not allow us to follow the displacement trend. This also leads to inadequate knowledge of the geo-mechanical processes leading to failures and hence the inadequate prediction of possible landslides [6].

The current work focuses on the temporal prediction of slope failure time on the slope scale, based on its kinematic parameters such as displacement and its derivatives. But such approaches are still not routinely adopted in risk management for the monitoring systems are not much economical. Even though the technique is expensive, its logically accurate forecasting allows us to avoid human losses, minimize property damage, and design adequate countermeasures. Generally, empirical and semi-empirical methods are used for predicting the time of failures of the slopes. The empirical function is usually derived from the results of laboratory creep tests and relates the observed surface displacements before failure to the time from slope failure (TSF). The present work systematically explains and compares the methods such as empirical and semi-empirical for forecasting the time of failure of slopes with their respective advantages and limitations.

2. Methods for Predicting the Time of Failure of Slopes Based on Kinematics

The logic behind the temporal prediction of the landslide is studied through the creep curve proposed by Terzaghi. It was assumed that the deformation or displacement processes of the slope surface take a long period so that it generally indicates that slope failure normally displays a time-dependent property. The predictions of the time of failure of slopes from the creep curve assumed that the slopes often experience displacements (Fig. 1) before the rupturing of the slopes [7]. Generally, there are three stages for a creep curve; primary creep, secondary creep, and tertiary creep.

a) Primary creep: The strain rate decreases logarithmically at this stage
b) Secondary creep: Constant strain rate region
c) Tertiary creep: Creep rate increases at this stage which leads to rupture

Mainly there are two methods based on kinematic parameters for predicting the time of failure of slopes.

A. Empirical Methods: These methods are based on the remark that the velocity of displacement increases considerably before the failure of slopes and typically extrapolate the failure time by geometric claims.
B. Semi-empirical Methods: The starting point of this method is a basic equation relating to the rate of displacement to the acceleration using certain empirical constants. Both of the above methods are usually referred to as sliding, toppling as well as compound landslides with no inherent limitations to the size, activity state and types of slope materials.

![Figure 1. Schematic representation of the three stages of creep curve](image)

2.1 Empirical Methods

The empirical methods for determining the time of failure of slopes are mainly relying upon the collected movement monitoring data of the slopes. The first notable contribution was from Saito and Uezawa in the year 1965 followed by Fukuzono in 1985 based on surface displacement and its acceleration rates.

Initially, Saito and Uezawa [8] recommended an empirical formula for finding creep rupture life of slopes based on the relationship between constant strain rate \( \dot{\varepsilon} \) and creep rupture life of slopes or time remaining before failure \( (t_r) \). They have measured the surface strain of slopes using proper devices and plotted the same and corresponding time in the log-log scale. The developed formula was based on the secondary creep curve and independent of the type of earth material, method of testing and the test results were appeared to be applicable in any part of the world.

\[
\log_{10} t_r = 2.33 - 0.916 \log_{10} \dot{\varepsilon} \pm 0.59 \tag{1}
\]

A modification on Eq. (1) was again introduced by Saito [9] in the year 1969 based on the tertiary creep curve and it demonstrated the relationship between creep rupture life and transient strain rate at the optional time. The creep rupture life \( (t_r) \) of the above equation was replaced by the remaining life of slope failure \( (t_r - t) \) and the constant values 2.33 and 0.916 were expressed in terms of \( \log a \) and unity. Then, Eq. (1) becomes;

\[
\log (t_r - t) = \log a - \log \dot{\varepsilon} \tag{2}
\]

Also, a modification on Eq. (2) was given by considering no strain rate at the time of \( t = t_0 \) and replaced strain rate with respect to displacement rate \( \dot{\varepsilon} = \frac{\Delta D}{D_0} \).

\[
\Delta D = D_0 a \log \frac{t_r - t_0}{t_r - t} \tag{3}
\]

Where, \( \Delta D \) is the relative displacement between two measured points and \( D_0 \) is the initial distance between two measured points. Further explanation on Eq. (3) was expressed through considering three equally placed points in the tertiary range of the creep curve (Fig. 2).

Based on the graphical approach, three equally spaced points along Y-axis were considered on the tertiary creep range \( (A_1, A_2 \text{ and } A_3) \) and they appear to have an equal difference of displacement \( (\Delta D) \). \( A_1 \) and \( A_3 \) \( (A_1' \text{ and } A_3') \) were projected to a line parallel to the time axis and passing through \( A_2 \). Two midpoints M and N were considered for the lines \( A_1'A_2 \text{ and } A_2A_3' \) and are projected \( (M' \text{ and } N') \) to a line passing through \( A_2 \) and parallel to the displacement axis. Then, two straight lines were drawn
through points $A_1', N'$ and $M'$ and the line through $M'$ was parallel to the time axis. Finally, the time of failure was obtained as the abscissa of the intersection of these two straight lines with that of the X-axis (time axis).

The empirical solution from the graphical approach was obtained by substituting the values of all three points of the creep curve on Eq. (3). i.e;

$$t_r = \frac{t_2^2 - t_1 t_3}{2t_2 - (t_1 + t_3)}$$

(Figure 2. Schematic interpretation of the failure time of slopes in the tertiary range of creep curve)

Fukuzono [10] in the year 1985 has proposed an empirical formula based on the accelerating nature of measured surface displacement rates. According to this method, there is a linear trend for the tertiary creep curve while approaching the time of failure of slopes. Fukuzono [10] has considered two outcomes during the onset of the acceleration of landslides and is illustrated in Fig. 3. That is; (i) velocity of displacement of slopes increases until its collapse (time of failure of slopes occurs when velocity approaches infinity or inverse of velocity becomes zero) and (ii) velocity decreases after an initial rapid increase in acceleration and thereafter reaches another safe equilibrium state (without landslide collapse). Fukuzono [10] developed an equation for finding out the acceleration or inverse velocity of slope movement by considering the effect of the constant load until failure. Also, has considered a linear correlation between the logarithm of velocity and logarithm of acceleration of the displacement of slope surface just before failure.

$$\frac{d^2x}{dt^2} = a \left(\frac{dx}{dt}\right)^\alpha$$

Where; $x$ is the slope surface displacement, $t$ is the time of measurement, $\frac{d^2x}{dt^2}$ and $\frac{dx}{dt}$ are the acceleration as well as the velocity of surface displacement, $a$ and $\alpha$ are the empirical constants; $\alpha$ has values in the range of 1.5 and 2.2 in this method. The integration of Eq. (5) for the range of $\alpha>1$ derives the formula for the inverse value of velocity $\left(\frac{1}{v}\right)$, i.e;
\[ \frac{1}{v} = a (\propto - 1)^{\frac{1}{\propto - 1}} (t_f - t)^{\frac{1}{\propto - 1}} \] (6)

The trend of the obtained curves varies with the value of \( \propto \): the plot becomes linear with \( \propto \) having a value of 2, convex when \( \propto > 2 \) and concave when value lies in between 1 and 2. Fukuzono [10] has also proposed a graphical approach based on the developed equation (Eq. 6) and it consists of plotting the inverse of the velocity versus time. The resultant plot shows a line which is parallel to the time axis during the time of equilibrium condition of the landslide. But as the velocity increases, the plot displays a line that intersects the X-axis (time axis) when velocity becomes infinity and the intersecting point gives the value of time of failure of slopes.

Figure 3. Graphical interpretation of the two outcomes during the onset of acceleration of landslides

Hayashi et al. [11] introduced a method to forecast the time of failure of slopes in the early period of the tertiary creep curve by separately considering two stages in the tertiary range of creep curve in the year of 1988. The first stage immediately follows the secondary creep range and the second stage consists of considering the start of failure of slopes in the final periods of the first stage up to the final collapse of slopes in the second stage. The study on the different stages of the curve has shown that the first stage takes more time of the early period of the creep curve. It has found that a higher value of the initial displacement of the slopes resulted in a quick collapse of the slopes and reduces the value of creep rupture life \( (t_r) \) and \( t_r \) is related with the elapsed time \( (\Delta t \text{- time to move initial unit length of displacement from the start of the tertiary creep}) \).

\[ t_r = a (\Delta t)^n \] (7)

Where; \( a \) and \( n \) are constants; \( a = 2.13 \) and \( n = 1.6 \)

Azimi et al. [12] suggested a graphical method in the year 1988 to solve the empirical formula given by Saito.\( \dot{\varepsilon} = \frac{a}{t_r - t} \)

The basic aim of the graphical procedure was to find out the specific time at which the rate of displacement (velocity) of the slope surface tends to infinity. The graphical approach consists of plotting the surface displacements versus time and considered separate segments on the curve having equal displacement values. From Fig. 4, as velocity increases, the time interval \( (\Delta t) \) between the selected segments gets reduced and finally \( \Delta t \) turns zero and failure of slope occurs. As for reducing the error and for improving the accuracy in prediction of the time of failure of slopes, more recent data were considered for this method.
Mufundirwa et al. [13] in the year of 2010 has proposed a relatively simple and quick SLOpe (SLO) method to forecast the failure time using the gradient or slope of the curve. The predictions were done based on an actual rock mass failure. The method assumed that the accelerating displacement rates of before prior to its failure are similar or comparable to the ultimate phase in the tertiary creep range. They adopted a basic equation representing the divergence phenomenon of strain or displacement in the final stage of the tertiary creep curve. ie;

$$\varepsilon = -B \log (t_f - t) + C$$  \hspace{1cm} (8)

Where; $\varepsilon$ represents strain, $t_f$ is the time of measurement, $t_f$ is the failure time, $(t_f-t)$ denotes the life expectancy of the slopes, B and C represents the empirical constants.

Eq. (8) was modified by differentiating it with time $t$ and replacing $\varepsilon$ with displacement $D$

$$\frac{dD}{dt} = \frac{B}{t_f-t}$$  \hspace{1cm} (9)

Where, $\frac{dD}{dt}$ denotes the velocity. The final solutions were obtained by multiplying both sides of the above equation with life expectancy $(t_f-t)$

$$tv = t_f v - B$$  \hspace{1cm} (10)

Then, a graph has drawn by plotting the velocity ($v$) in the X-axis and $vt$ along the Y-axis (Fig. 5). The time of failure of the slopes ($t_f$) is calculated as the angular coefficient of the line.

Figure 4. Displacement behaviour of unstable slopes in the final stages of failure

Figure 5. SLO method approach to determine the failure time of slopes
tv represents a dependent variable and v represents an independent variable (linear regression), B is the intercept.

Carla et al. [6] improvised the Inverse Velocity Method (INV) proposed by Fukuzono [10] by introducing data smoothing in inverse velocity values. As the Fukuzono’s [10] suggestion on forecasting the time of failure of slopes depends on the inverse value of a derivative parameter, the predictions can be hampered by noises in the measurements. Therefore, this method has progressed by practicing different filters with the measured velocity and time of four actual slope failures. They have used the two most common and easy to use smoothing algorithms, that is, measured values of velocities are filtered with moving average and exponential smoothing.

a) Short-term simple moving average (SMA)

Smoothed velocity at time t is;
\[
\bar{V}_t = \frac{v_t + v_{t-1} + \ldots + v_{t-(n-1)}}{n}; n=3
\]  

b) Long-term simple moving average (LMA)

\[
\bar{V}_t = \frac{v_t + v_{t-1} + \ldots + v_{t-(n-1)}}{n}; n = 7
\]  

c) Exponential smoothing function (ESF); smoothing factor \(\beta = 0.5\)

\[
\bar{V}_t = \beta \cdot v_t + (1 - \beta) \cdot \bar{V}_{t-1}
\]  

Where ‘n’ is the number of samples measured and it varies with the quality of the measured values, landslide velocity as well as noises in the measured quantities. They have found that different filters show different characteristics according to the type of the landslides and hence simultaneous applications of both short term and long term moving averages were studied in this method. Also, after the successful smoothing of the measured velocity, they have introduced a failure window (\(t_{fw}\)) within which the occurrence of slope failure is considered to be more probable. Failure windows were developed based on both SMA and LMA, therefore, two different values for the time of failure of slopes have been obtained (\(t_{f(SMA)}\) and \(t_{f(LMA)}\)) with a difference of \(\Delta\). They have assumed that if \(t_{f(SMA)} < t_{f(LMA)}\), \(t_{fw}\) has to be determined in between \([t_{f(SMA)} - \frac{\Delta}{2}; t_{f(LMA)} + \frac{\Delta}{2}]\). The proposed method also helped to determine the starting of acceleration of the landslides as well as the changes in the deformation rates of the slopes.

2.2 Semi-empirical Methods

Semi-empirical methods are partially empirical. Because it uses a part of the experimental results and also involves some assumptions, approximations or generalizations to simplify the empirical calculations, or to obtain good results following experimental observations.

Voight [14] in the year 1988 has proposed the mathematical generalizations for Fukuzono’s [10] solution. He has followed a basic equation provided by Fukuzono [10] regarding the behaviour of materials in the final stages of collapses.ie;

\[
\hat{\Omega} = A \hat{\Xi}^\infty
\]  

Eq. (11) describes the proportionality between the logarithm of acceleration and the logarithm of the velocity of the displacement of the ground surface. Where; \(\hat{\Omega}\) and \(\hat{\Xi}\) denotes the velocity and the acceleration, a and \(\infty\) are the empirical constants. Also, this method founded out many other relations from Eq. (11) and the integration of Eq. (11) gives the expression for \(\hat{\Omega}\) by considering \(\hat{\Omega} = \hat{\Omega}_0\) at \(t = t_0\) (for \(\infty = 1\)). ie;

\[
\hat{\Omega} = \hat{\Omega}_0 e^{A(t-t_0)}
\]  

As a contradiction to Fukuzono’s [10] findings, Voight [14] has assumed that slopes collapse when \(\hat{\Omega}\) approaches an estimated threshold value (\(\hat{\Omega}_t\)). That is;
\[ \dot{\Omega} = \left( A(\alpha - 1)(t_f - 1) + \dot{\Omega}_f^{(1 - \alpha)} \right)^{\frac{1}{1 - \alpha}}; \text{for } \alpha > 1, \alpha \neq 2, \alpha > 1, \alpha \neq 2 \]  

Equation (13)

Voight [14] also derives an equation by considering the findings of Fukuzono [10]. That is, failure occurs when \( \dot{\Omega} \) approaches infinity. ie;

\[ t_f = \frac{\dot{\Omega}_f^{1 - \alpha} - \dot{\Omega}_{f(1 - \alpha)}}{A(\alpha - 1)} + t \]  

Equation (14)

The main drawbacks of this method involve the assumption that deformation rates and loading conditions in the slopes are time-invariant. But it is not true in the real sense. Also, he followed the same values as that of Fukuzono [10] for constants A and \( \alpha \) by neglecting the fact that A and \( \alpha \) can never remain as constants; it keeps on changing with different types of landslides cases.

Hao et al. [15, 16] has provided an alternative expression of Voight’s relation by considering the real facts of changes in deformation rates of slopes with changes in stress conditions. This method is widely used to identify the accelerating preceding trends before the collapse of the slopes. The main feature of this method over other studied methods involves the prediction of failure time without initially finalizing or fitting the values of A and \( \alpha \) (for all \( \alpha > 1 \)). Because the accuracy and precision in forecasting depend on the fluctuation in the value of \( \alpha \). According to the assumptions, he derives an equation and developed a graphical approach (Fig. 6) showing the relation between the ratio of displacement rate to acceleration \( \dot{\Omega}\dot{\Omega}^{-1} \) with the time of failure of slopes \( t_f \).

\[ \dot{\Omega}\dot{\Omega}^{-1} = C(t_f - t) \]  

Equation (15)

Where; \( C = \alpha - 1 \)

**Figure 6.** Graphical approach given by Hao et al. without the initial fitting of empirical constants

From Fig. 6, the time of failure of slopes is predicted by extrapolating the line of \( \dot{\Omega}\dot{\Omega}^{-1} \) against time until it reaches zero. Also, from the above graph, the linearly decreasing trend of \( \dot{\Omega}\dot{\Omega}^{-1} \) with time and slope value (C) of \( \alpha - 1 \) can be studied.

3. Discussions

The following results were obtained after studying and comparing the empirical and semi-empirical methods for forecasting the time of failure of slopes.

3.1 Comparative Study of Landslide Forecasting Methods

The method with better performance and high reliability over other studied methods are more difficult to determine. Most of these methods are not much applied in any real case and hence the evaluation of a better method is not yet possible. Also, the methods which find applications in real case hazards are done after the event to study the factors that triggered it. Table 1 shows a collected list of research
papers mentioned about the real case applications of some of the above-studied methods. From Table 1, it can be concluded that one of the most used methods is Fukuzono’s (1985) [10] method which is an extension of Saito’s (1969) [9] empirical formula. Both these methods are considered as the most widely spread techniques as the prediction of the time of failure of slopes was based on the accelerating creep theory. Thereafter, many other authors studied based on the same theory from different perspectives. According to this concept, the failure of the slopes is assumed to occur when the extrapolated trend line of inverse velocity versus time graph approaches the time axis or zero. The major limitation of the method suggested by Fukuzono [10] is the linear trend of the graph \( \propto = 2 \) approaching the time axis. Then, a method more conservative than the INV method was suggested by Voight [14], also find some applications in the real cases of geo-hazards. But the assumption of time-invariant loading conditions and deformation rates demotivated the large scale use of this method. From studying also these methods, Fukuzono’s (1985) [10] method has provided some assumptions about the onset of accelerations, trend line behaviours as well as it appears to be more graphically approachable. However, Fukuzono’s [10] method got affected by the noises in the measured displacement data due to the dependence on an inverse value of a derivative parameter.

### Table 1. List of Applications of Empirical and Semi-Empirical Methods

| Research Work | Application area | Applied prior to the event | Forecasting Method Used |
|---------------|------------------|---------------------------|-------------------------|
| Cruden & Masoumzadeh, 1987 [17] | Open-pit mining | No | Saito 1969 |
| Suwa 1991 [18] | Slope failure | Yes | Saito 1969 |
| Cornelius and Voight, 1994 [19] | Volcanic eruption | No | Voight 1988 |
| Hung and Kent, 1995 [20] | Open-pit mining | Yes | Fukuzono 1985 |
| Hutchinson, 2001 [21] | Slope failure | No | Fukuzono 1985 |
| Zvelebil and Moser, 2001 [22] | Slope failure | Yes | Fukuzono 1985 |
| Petley, 2005 [23] | Slope failure | No | Fukuzono 1985 |
| Krahenbuhl, 2006 [24] | Slope failure | Yes | Fukuzono 1985 |
| Lavallee et al., 2008 [25] | Volcanic eruption | No | Voight 1988 |
| Rose and Hungr, 2007 [26] | Open-pit mining | Yes | Fukuzono 1985 |
| Casagli et al., 2009 [27] | Volcanic eruption | Yes | Fukuzono 1985 |
| Gigli et al., 2011 [28] | Slope failure | Yes | Fukuzono 1985 |
| Venter et al., 2013 [29] | Open-pit mining | No | Fukuzono, 1985, Mufundirwa et al. |
| Osasan and Stacey, 2014 [30] | Open-pit mining | Yes | Fukuzono 1985 |
| Mazzanti et al., 2015 [31] | Slope failure | No | Fukuzono 1985 |
| Dick et al., 2015 [32] | Open-pit mining | No | Fukuzono, 1985, Mufundirwa et al. |
| Manconi and Giordan, 2016 [33] | Slope failure | No | Fukuzono 1985 |
| Intrieri and Gigli, 2016 [34] | Volcanic eruption, Slope failure, open-pit mining | No | Saito, 1969, Fukuzono, 1985, Mufundirwa, 2010 |
| Sattele et al., 2016 [35] | Slope failure | Yes | Fukuzono 1985 |
| Loew et al., 2017 [36] | Slope failure | Yes | Fukuzono 1985 |
| Carla et al., 2017b [37] | Open pit mining | No | Fukuzono 1985 |
| Carla et al., 2017a [6] | Slope failures | No | Fukuzono 1985 |
| Carla et al., 2018 [38] | Open pit mining | No | Fukuzono 1985 |
| Corcoran and Davies, 2018 [39] | Materials science | No | Fukuzono, 1985 & Voight, 1988 |
| Intrieri et al., 2018 [40] | Slope failure | No | Fukuzono 1985 |
| Kothari and Momayez, 2018 [41] | Open-pit mining | Not available | Fukuzono 1985 |

3.2 Applications of Landslide Forecasting Methods

Table 1 shows a listed collection of research papers that have mentioned the real case applications of the empirical and the semi-empirical methods for the time of failure prediction of slopes. As mentioned earlier, Fukuzono’s (1985) [10] approach was the most widely accepted methodology mainly because of the quick and simple approaches to use. The semi-empirical methods find more applications in some volcanic eruptions based on slope failures. Most of the semi-empirical methods
have been successfully utilized in the mining industry. A huge amount of economic as well as human losses were considered to associate with large open mine pits. Also, the endless excavation procedures for metal, oil, and other material extractions negatively affected the stability of shallow as well as deep slopes. Also, the elements lying on or near the slopes experience high risk. There are many advanced monitoring networks and equipment that are placed over these slopes to find the rock and other material exposure features and alignments changes over the surface. The individuals controlling these systems are also at risk due to the instability of slopes caused by the excessive mining processes.

The concerns over public and property safety are proportionally rarer these days. The principal reason is probably due to the absence of early forecasting or alert systems required to place in areas prone to slope failure. Most of the real case events mentioned in the table is caused by the open-pit mining industry. Generally, landslides are analyzing without having any constraints over the material type, type of landslides, the current state of activity of the slopes whether it is failed for the first time or it is a reactivated failure case, etc.

3.3 Limitations of the Landslide Forecasting Methods
The lead of forecasting is considered as the presence of early warning systems or alert thresholds in the landslide-prone areas. It is necessary to find some better performing and economic tools for alleviating risk by proper protection or placement of elements in danger. Proper monitoring and studies over slopes, prone to failure, are necessary for a long period before failure. But the short term monitoring of the displacement trend of slopes is not often providing any alert signals or behavioural changes in deformation trends of slopes so that not much time is getting for evacuating the prone areas. The lack of knowledge to understand the pre-failure changes in slopes is also act as a leading factor intensifying the natural hazards.

Despite this, several empirical methods for predicting the failure time of slopes based on its surface displacement rates have been developed by Saito 1969, Fukuzono 1985 [10], Azimi et al. 1988 [12], Hayashi et al. 1988 [11], Mufundirwa et al. 2010 [11], and Carla et al. 2017 [6]. Further, Voight [14] in the year 1988 provided a mathematical generalization for Fukuzon’s [10] solution by stating the importance of considering the variation in the value of empirical constant from 2. As a contradiction to all these facts, Hao et al. [15,16] in the year 2017 put forward the idea of landslide forecasting without the initial fitting of the empirical constants A and ∞. This method finds applications in rockslides and volcanic eruptions.

Also, these studied methods are still finding difficulties due to noises in measurements produced by the presence of an inverse value of a derivative parameter, inaccuracy in collecting the movement monitored data, invisible accelerating trends, etc. The basic steps to follow while forecasting the failure time of slopes includes the requirement of suitable noise filters as well as persons with a high degree of experience and knowledge in elucidating the collected data. Then, it is necessary to find the time of starting of the acceleration trend of slope surface displacement. Similarly, proper detection of the new stable equilibrium of the slopes after or before failure and the time at which the final acceleration of the creep has stopped is also important because most of the above - studied methods are depending on the acceleration behaviour of slopes. So that immediate decelerations can trouble the failure time predictions. The current trend in practicing the forecasting technique appears to be involving more than one technique and making conclusions according to the average or more secure forecast.

3.4 Advanced Technologies for Landslide Forecasting
The future goals in slope failure prediction will be advanced by technological development in monitoring equipment and technique. Some of the advanced technologies used for landslide forecasting are presented in the following session.
3.4.1 Interferometric Synthetic Aperture Radar (GB-InSAR) [32]: Interferometric Synthetic Aperture Radar (InSAR) satellites are radar technique used for remote sensing. The synthetic aperture radar images are used to map surface deformations and their digital elevations.

3.4.2 Wireless Sensor Networks (WSN) [42]: WSN technology constitutes collection of spatially distributed and dedicated sensors to track and record environmental physical conditions and coordinates all the data collected at a central location. The creation of Wireless Sensor Networks (WSN) performing ranging measurements using the ultra-wideband signal to transfer data could yield interesting results and thereby avoiding the costs associated with individual sensors.

3.4.3 Radio Frequency Identification (RFID) [43]: For early warning applications, it is a promising technology based on tags that can be mounted over slopes with minimal environmental impact and determine their relative displacement with high temporal resolution.

3.4.4 Global Positioning System (GPS) chips [44]: GPS chips provide users with instant location and time information anywhere on earth and available at a lower cost has been used for landslide early warning systems. These systems use many satellites and it transfers those data using high-frequency radio signals.

4 Conclusions
In short, Geo-hazards are a major life-threatening event and a huge financial loss to the geotechnical sector. Since the complete eradication of landslide failures are difficult, the maximum reduction in mortality and economic losses is possible through accurate prediction of failure time of slopes. Therefore, an effective attempt to forecast the failure time of rock as well as soil mass is necessary for this current scenario. However, the failure time prediction of landslides involves a large number of variables and parameters affecting landslide behaviour and its triggering. This appears as one of the most difficult problems with slope stability analysis and it was considered as the key focus of all methods studied here. Investigators have used several direct or indirect approaches that produce quantitative and/or qualitative assessments. In this work, we have focused on kinematics-based landslide forecasting methods such as empirical and semi-empirical methods. The present work systematically describes the various empirical and semi-empirical methods of landslide prediction suggested by various researchers. The advantages and limitations of each method are described in the present work, along with a comparative evaluation. The following important conclusions have been drawn from reviewing some important research works based on kinematic parameters on the time of failure prediction of landslides.

- From the reviewed landslide forecasting methods, it is seen that some methods performed better than others, but not a single method has been shown to be effective in all situations
- Although some methods performed better than others, no single method proved to be superior in all conditions.
- The most reliable strategy for landslide forecasting is to use more than one methodology and make final decisions based on average or best predictions.
- Most of the studied methods were based on the accelerating trend of deformation rate in the tertiary creep range.
- A universal method has not yet been established to identify the exact point where the transition between secondary and tertiary creep occurs.
- The method given by Fukuzono[10] (INV method) appears to be the most graphically communicative and is based on the fact that the inverse of displacement velocity is a significant factor in the slope failure time process.
- The traditional INV technique gave initial insecure predictions due to the convex appearance of the trend line. But as it ranges closes to failure, it appears to become more reliable and linear so that the proper evacuation of the affected areas is difficult and not practical.
Short term monitoring of the displacement trend of slopes is not effective for the timely predictions of slope failures. Effective forecasting can be carried out through the continuous measurement of relative displacement of the slopes. Most of the studied methods to predict the failure time of the slopes were applied before the actual failure of the slopes. The predictability of a landslide relies on its kinematics and then on the factors that influence it like the geological features of the slope, other external disturbance, local and natural effects, etc. The scope of future research in temporal prediction of landslides is:

- Investigation of the relationship between kinematic parameters and other geological, geotechnical, and geomorphological aspects of slopes.
- A collaborative study of different areas of research such as geo-mechanics, geology, and advanced techniques in remote sensing
- Prediction of slope instability using machine learning techniques
- Utilization of wireless sensor networks for tracking and recording the surface changes of slopes

The methods studied in this work should serve as guidance and are not a complete solution for the prediction of geo-mechanical failure-time. Nowadays more advanced techniques and types of equipment are available to track the displacement rates in slopes and the better usage of those are a partial solution to the problems associated with a natural disaster.

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