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Slope stability and seepage analyses of earth dam embankment by empirical and numerical modelling techniques

Stabilité des pentes et analyses des infiltrations des remblais de barrage en terre ultilisant des techniques de modélisation empiriques et numériques

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ABSTRACT: Many communities in northern Nigeria are in serious need of supplementary water supply systems to augment the scanty rainfall in the region with a population of majorly farmers who face a lot of hardship due to acute shortage of water in most part of the year. The aim of this study is to provide a well-designed and reliable dam for irrigation water supply. To achieve this aim, this study focused on the analysis of the stability of an earth dam embankment and its seepage, which is very vital for the safety, stability and economic (optimal) design of the dam. The conventional methods of slope stability analysis have major limitations which were addressed by numerical modelling techniques. This study was carried out using some analytical methods and then SLOPE/W and SEEP/W numerical modelling programs. The stability of the embankment slope was also modelled for rapid drawdown conditions based on worst case scenario. The safety factor results show that the embankment is safe from slope failure having a minimum safety factor value of 2.302. A minimum safety factor result of 1.416 was observed after a worst case scenario of rapid drawdown from the maximum anticipated flood water height of 7.6 m to 0 m in 24 hours which is satisfactory. The results of maximum hydraulic velocity and rate of seepage of 4.15E-04 m/sec and 1.27E-04 m^3/sec respectively were indication of need for sufficient compaction and careful selection of core material with a very low permeability for adequate design against piping failure.

RÉSUMÉ: De nombreuses communautés du nord du Nigéria ont profondément besoin de systèmes d'approvisionnement en eau supplémentaires pour augmenter les faibles précipitations dans la région avec une population majoritairement d'agriculteurs confrontés à de graves difficultés en raison d'une grave pénurie d'eau pendant la majeure partie de l'année. Le but de l'étude est de fournir un barrage bien conçu et fiable pour l'approvisionnement en eau d'irrigation. Pour archiver cet objectif, cette étude s'est concentrée sur l'analyse de la stabilité d'un remblai de barrage en terre et de son infiltration, ce qui est très vital pour la sécurité, la stabilité et la conception économique (optimale) du barrage. Les méthodes conventionnelles d'analyse de la stabilité des pentes ont des limitations majeures qui ont été abordées par les techniques de modélisation numérique. Cette étude a été réalisée à l'aide de certaines méthodes analytiques et des programmes de modélisation numérique SLOPE / W et SEEP / W. La stabilité de la pente du remblai a également été modélisée pour des conditions de rabattement rapide basées sur le pire des scénarios. Les résultats du facteur de sécurité montrent que le remblai est à l'abri de la rupture de talus avec une valeur minimale du facteur de sécurité de 2,302. Un résultat de facteur de sécurité minimum de 1,416 a été observé après le pire scénario de rabattement rapide de la hauteur maximale prévue de la crue de 7,6 m à 0 m en 24 heures, ce qui est satisfaisant. Les résultats de la vitesse hydraulique maximale et du taux d'infiltration de 4.15E-04 m / sec et 1.27E-04m3 / sec respectivement indiquaient la nécessité d'un compactage suffisant et d'une sélection rigoureuse du matériau de noyau avec une très faible perméabilité pour une conception adéquate contre la défaillance de tuyauterie.

KEYWORDS: Earth dam embankments; Factor of safety; Numerical modelling; Seepage analyses; Slope stability.

1 INTRODUCTION

Many communities in Nigeria are subject to long time dry period of no rainfall. Yet, the only business of majority of these communities is farming as they are mostly rural people with no formal education. One of these communities is Iyatawa, in Rimi Local Government Area of Katsina State, Nigeria, which needs well designed and reliable dam for irrigation purpose in order to ensure safety of and wellbeing of the community. The slope stability analyses in geotechnical engineering have followed closely the developments in soil and rock mechanics as a whole. Slopes either occur naturally or are engineered by humans. The core competence of a civil engineer is developing reliable and effective systems for the society by mitigating risk and reducing failure. This includes forecasting and prevention against catastrophes due to natural hazards. Natural hazards cause significant damage on human life and economic loss. To minimize these enormous damages, especially those caused by geohazards, an appropriate preventing techniques are needed and reliability analysis relating geohazards should be adopted (Cheng *et al.,* 2007).

To quantitatively assess the stability of a slope in an engineered slope stability failure mechanisms analysis, a parameter F known as factor of safety is used which is simply the ratio of the resistance forces to the gravity forces parallel to slope.

A value of F greater than unity indicates stability, whereas F less than 1 implies instability. F value of 1.5 is generally reported to be satisfactory in the literatures (Duncan, 1996). Thus, the transition between stability to collapse may be envisaged mathematically as a decrease in the factor of safety to values below unity. The quantitative determination of the stability of slopes is necessary in a number of engineering activities, such as: (a) the design of earth dams and embankments, (b) the analysis of stability of natural slopes, (c) analysis of the stability of excavated slopes, (d) analysis of deep-seated failure of foundations and retaining walls, (e) open pit mining, (f) road cuts. Conventional forms of slope stability analysis are limited to simplistic problems in the scope of application, encompassing simple slope geometries and basic loading conditions, and as such, provide little insight into slope failure mechanisms (Bojorque *et al.,* 2008).

Many soil slope stability problems involve complexities relating to geometry, material anisotropy, non-linear behaviour, in-site stress and the presence of several coupled processes (e.g. pore pressure, seismic loading, etc.). To address these limitations, numerical modelling techniques have been forwarded to provide approximate solutions to problems, which otherwise, would have not been possible to solve using conventional techniques. Advances in computational methods and the availability of relatively inexpensive commercial numerical modelling codes means that the simulation of potential soil slope stability failure mechanisms could, and in many cases should, form a standard component of a soil slope and seepage investigation (Duncan, 1996). Numerical modelling is a powerful mathematical tool that makes it possible to solve complex engineering problems. The constitutive behaviour of soils can be successfully modelled with numerical analyses using some basic soil properties as input data. The finite element method is one of the mathematical methods in which continuous media is divided into finite elements with different geometries (Salahudeen and Aghayan, 2018). It provides the advantage of idealizing the material behaviour of the soil, which is non-linear with plastic deformations and is stress-path dependent, in a more rational manner (Salahudeen et al., 2017).

Dams (dykes) are constructed for various purposes like flood control, navigation, water source, recreation, power generation, etc. Earth dams have always been associated with seepage as they impound water in them. The water seeks paths of least resistance through the dam and its foundation. Seepage will become a problem only if it carries dam materials along with it. Seepage must be controlled to prevent the erosion of embankment or its foundation. Different methods like analytical, electrical analogy and flownet have been used to study and monitor seepage in dams (Mergili *et al.*, 2014). Embankment dams are more common in Nigeria than any other type of dams because they only need ordinary technology construction method utilizing cheap raw soil materials that are locally available (Salahudeen et al. 2019a). Some of the important factors causing failure of embankment dam are slope failures, settlement and seepage through the embankment materials and hence their analyses in embankment dam design is of greater importance. Recently, Finite Element Method (FEM) is being used by geotechnical engineers for the seepage analysis of embankment dams (Rouaiguia and Dahim, 2013). Olonade and Agbede (2013) performed a computer simulation of the groundwater flow through a porous medium in the Northern region of Nigeria.

In this study, the slope stability and seepage analysis of an earth dam was performed using SLOPE/W and SEEP/W respectively in GeoStudio, a geotechnical engineering modelling software packages. The objective of the study is to analyse the stability and seepage of a proposed dam site at Iyatawa, in Rimi Local Government Area of Katsina State, Nigeria, in order to ensure both safety and sustained economic development of the community. This analysis of the stability and seepage of the dam embankment is very vital for the safety, stability and economic or optimal design of the dam.

2 MATERIALS AND METHODS

2.1 *Materials*

2.1.1 *Soil*

The soil samples used for this study were collected from the proposed Iyatawa Dam and Irrigation Project located in Iyatawa town, Rimi Local Government Area in Katsina State, Federal Republic of Nigeria. The soil samples were obtained from the dam site specifically using disturbed sampling method from four trial pits dug to a depth of 3.0m below the top soil to avoid organic matter influence. The samples were labelled TP1 to TP4. Some of the soils from each trial pit were sealed in plastic bags and put in sacks to avoid loss of moisture during transportation.

2.1.2 *Background Information and Geology of the Study Area*

Katsina State is located at the North-West geopolitical zone of the Federal Republic of Nigeria. The study site, a proposed dam site in Iyatawa, in Rimi Local Government Area of Katsina State is bordered by Kuntawa in the North, Mahuta (Zango Kanya) in the West, Remawa in the East and Take-Tsimi in the South. The study area is close to the Cika-Koshi town that harbours the Are dam in Charanchi Local Government Area of Katsina State. The project area is located very close to Iyatawa town located at Latitude 12^0 47.198’N of the Equator and Longitude 007^0 43.268’E of the Greenwich Meridian with a population of majorly farmers with some few petty traders. The area falls within the Karaduwa River Basin which is situated within the Tagwa/Gani plains both of which fall under the Kano plains and inundates a large expanse of farm with its numerous tributaries. The vegetation of the study area is typical Sudan Savannah characterised by sparse shrubs, interrupted by large isolated trees. Katsina State lies in the great Hausa plains of northern Nigeria that is composed of basement complex rock that covers over 50% of the Nigerian landmass (Ola, 1983). Generally, the topography is gently undulating with an elevation of between 305m-610m with isolated inselberge and residual iron stone capped hills that lie between 610m – 905m above mean sea level interspersing the area (Salahudeen and Aghayan, 2018).

The continental sediments of Katsina – Daura plains consist of feldspatic clayey standstones and grits with small basal pebble beds. The sediments have a maximum thickness of about 100m (Duprax,1994) and regional dip is to the north – west. The sediments thin to the south and in places, only the pebble beds remain on the higher interfluves. The southern boundary is diffuse and outliers are frequent, south of the main body. The younger alluvium occurs along the rivers within the present floodplain. Recent alluvial deposits are associated with the floodplains of the major rivers in the area. The soil of Katsina State follows its geology and geomorphology. The soil types found here range from shallow and moderately deep to very deep loamy, loamy-sand and sand-loamy soils.

2.2 *Methods*

Laboratory tests were performed to determine the index properties and strength parameters of the soil in accordance with BS 1377 (1990).

2.2.1 *Numerical Methods*

Using numerical modelling technique, slope stability and seepage analyses were performed using Geo-Slope as detailed below.

Slope Stability Analysis: The SLOPE/W package for slope stability simulations in GeoStudio was used for modeling the slope stability of the embankment at its maximum anticipated flood water height (11 m) and during rapid drawdown conditions based on worst case scenario. Details on the procedure for modelling using SLOPE/W can be found in Geo-Slope Manual (2018). The input parameters used in modelling the dam embankment in SLOPE/W and SEEP/W are the derived soil parameters from the laboratory results.

Slope Stability due to Rapid Drawdown: Since fast reduction of the reservoir level due to tidal effect or fast reduction in flood water can lead to failure of the dam due to high pore water pressures that built up and remain in the dam, a transient groundwater flow analysis was used to model the rapid drawdown numerically in SLOPE/W. The pore pressure resulting from the groundwater flow analysis were transferred to the deformation analysis and used in the slope stability analysis of the reservoir embankment of the dam. This was done by first considering situation when the dyke is at its maximum anticipated flood water height (7.6 m) and rapidly drawdown to 3.8 m. Secondly, the worst case scenario of rapid drawdown from the maximum anticipated flood water height of 7.6 m to 0 m in 24 hours period.

Seepage Analysis: For modelling the seepage analysis of the dyke embankment, the SEEP/W package for seepage analysis simulations in GeoStudio was used.Details on the use of SEEP/W package for seepage analysis can be found in Geo-Slope Manual (2018).

2.2.2 *Analytical Methods*

Slope Stability Analysis: Two types of analytical procedures of slope stability analysis were used in this study. The first one is the total stress or mass procedure in which case the mass of the soil above the surface of sliding is taken as a unit. This procedure is useful when the soil that forms the slope is assumed to be homogeneous. This method is intended to estimate the stability of the embankment immediately after its construction. Therefore the undrained values of the strength parameters were used. In spite of the imperfections of this method, it can be suitable for an engineered slope like a dam embankment whose materials are borrowed with standard predetermined properties. In this method, total stress analysis was performed to determine the factor of safety (F) through the disturbing and restoring moments taken about the centre of rotation as presented in Eq. 1.

$$F = \frac{Restraining\ moment}{Disturbing\ moment} = \frac{c_u r^2 \theta}{We} \qquad (1)$$

The second analytical method used is the method of slice. In this procedure, the soil above the surface of sliding is divided into a number of vertical parallel slices. The stability of each slice is calculated separately. This is a versatile technique in which the nonhomogeneity of the soils and pore water pressure can be taken into consideration. It also accounts for the variation of the normal stress along the potential failure surface. However, among the several methods of slices commonly used, the Michalowski (2002) was adopted in this study. Michalowski (2002) used the kinematic approach of limit analysis to analyse slopes with steady-state seepage. The fundamentals of the ordinary methods of slices assumed that the pore water pressure is zero. However, for steady-state seepage through slopes, which is the situation in many practical cases, the pore water pressure must be considered when effective shear strength parameters are used.

Seepage Analysis: The solution to seepage problem generally referred to as Schaffernak's solution with Casagrande's correction was used in this study. The hydraulic conductivity of the compacted material of which the earth dam was made was determined from a general model (see Eq. 2) proposed by Salahudeen et al. (2019b) which is a simplified model derived from the Carrier (2003) modified Kozeny-Carman equation.

$$k = 0.0371 - 0.0091C_u - 0.145C_c + 0.592D_{50} \qquad (2)$$

Where: k= permeability (cm/s), C_u = coefficient of uniformity, C_c = coefficient of gradation, D_{50} = effective size through which 50% of the soil samples passed.

The rate of seepage, which is the maximum flux was determined from Eq. 3.

$$q = kL\ tan\alpha\ sin\alpha \qquad (3)$$

Where

$$L = \frac{d}{\cos\alpha} - \sqrt{\frac{d^2}{cos^2\alpha} - \frac{H^2}{sin^2\alpha}}$$

Note that L is the distance from the exit point of the phreatic line to the heel of the dam embankment; d is the horizontal distance from the beginning of the parabolic free surface to the heel of the dam embankment; H is the height of water; α is the heel inclination angle and q is the rate of seepage per unit length of the dam.

3 RESULTS AND DISCUSSION

3.1 *Properties of the Soil*

Laboratory tests performed show that the soil samples can generally be classified as A-3 soil according to the AASHTO (1986) classification system and clayey sand (SC), using the Unified Soil Classification System, USCS (ASTM, 1992). The natural soil has low moisture content of an average of 14 % with an average of 20% of the soil particles passing through the BS. No 200 sieve. Table 1 shows summarized properties of the soil samples.

Table 1: Properties of the Soil from Laboratory Tests

Property	Quantity			
	TP1	TP2	TP3	TP4
% passing BS No 200 sieve	22.5	17.15	27.8	15.05
Natural moisture content, %	15	14	13	16
Degree of saturation, %	68	70	62	60
Void ratio	0.518	0.496	0.612	0.536
Bulk density, Mg/m3	1.962	1.863	1.759	1.812
Cohesion, kN/m2	5	9	3	13
Friction angle, degree	22	19	25	18

3.2 *Particle Size Distribution of the Soil Samples*

The particle size distribution curves for soil samples used for this study are shown in Figure 1. It was observed that the particle size distribution curves do not extend to the fine particle size limits much. In fact, as presented in Table 1, only an average of about 20% passes through the BS. No 200 sieve thereby showing that the particles are mostly coarse in nature (Salahudeen and Sadeeq, 2017). Classification of the soils further revealed that the soils are A-3 soil and clayey sand. Based on this sieve analysis results, it is expected that the soil, which are coarse, will have relatively high values of hydraulic conductivity well associable with clayey sands.

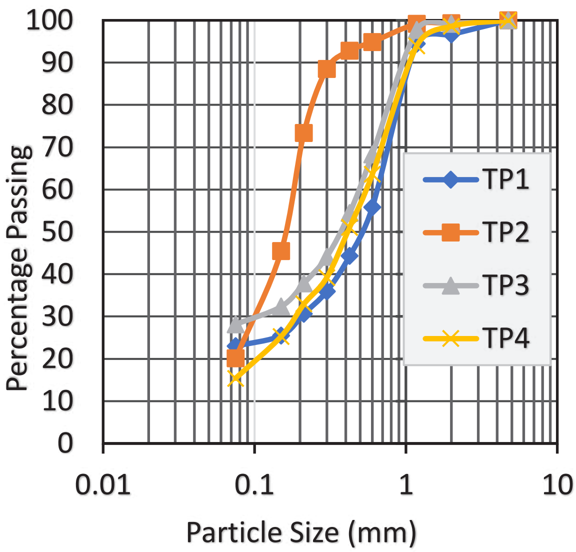

Figure 1: Particle size distribution curve

3.3 *Slope Stability Analysis at Maximum Flood Level*

The factor of safety results of simulation of slope stability using SLOPE/W in Geo-Studio numerical modelling code are presented in Figures 2. The safety factor results based on numerical technique show that the embankment is safe having a minimum safety factor value of 2.302 at TP1 and a maximum value of 2.821 at TP2. When an embankment has a factor of safety value of 1.0, it implies that equilibrium is just attained and any value below that 1.0 is an indication of lack of safety towards failure. Safety factor value above 1 is an indication of safety but too high value of safety factor is an indication of uneconomical design. An optimal value of slope safety factor of 1.5 is generally reported in the literatures. Results of safety factor using the total stress analytical method generally yielded high values. Using the total stress method, a minimum safety factor value of 1.877 at TP3 and a maximum value of 7.894 at TP4 that have the lowest and highest soil cohesion values respectively. This is not unconnected to the fact that the method was developed to determine the stability of the embankment immediately after its construction using the undrained values of the strength parameters which are usually higher than the effective values. The method also over rely on the soil's undrained cohesion value. The second analytical method of slices yielded the lowest values. It yielded a minimum safety factor value of 1.313 at TP1 and a maximum value of 1.527 at TP4 that have the lowest and highest amount of fines respectively. It may be as a result of being a versatile but highly conservative technique in which the nonhomogeneity of the soils and pore water pressures are been specifically considered. The method also accounts for the variation of the normal stress along the potential failure surface. More so, the Michalowski (2002) slice method adopted in this study used the kinematic approach of limit analysis to analyse slopes with steady-state seepage through slopes in which the pore water pressure was considered when effective shear strength parameters were used. This is the situation in many practical cases and therefore making the method an effective approach to slope stability problems.

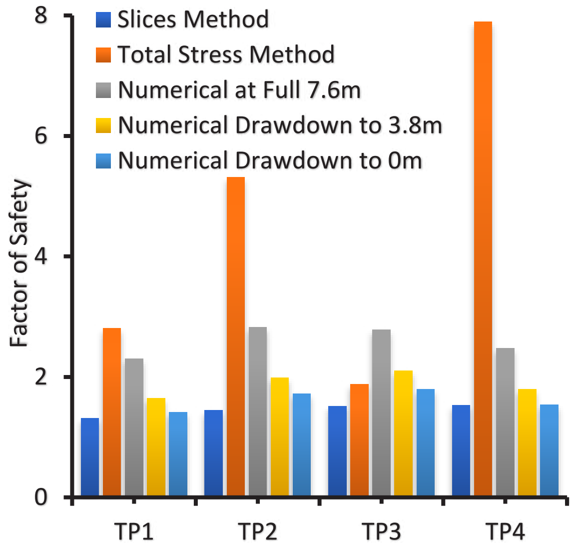

Figure 2: Factor of safety values

3.4 *Slope Stability Analysis under Rapid Drawdown*

In this study, a transient groundwater flow analysis was used to model the rapid drawdown numerically in SLOPE/W. This was done by first considering situation when the dyke is at its maximum anticipated flood water height (7.6 m) and rapidly drawdown to half way of 3.8 m. Secondly, the worst case scenario of rapid drawdown from the maximum anticipated flood water height of 7.6 m to 0 m was considered. A minimum safety factor of 1.416 was observed in TP 1 after a rapid drawdown from the maximum anticipated flood water height of 7.6 m to 0 m which is satisfactory although a little below the 1.5 value reported by Duncan (1996) in the literatures to be the minimum acceptable value of safety factors for slope stability. The factor of safety results of simulation of slope stability due to rapid drawdown are presented in Figures 2.

3.5 *Seepage Analysis*

Seepage analysis was performed using SEEP/W in GEO-STUDIO. The results of maximum hydraulic velocity and rate of seepage (flux) through a line around the middle of the embankment cross section are presented in Figures 3 and 4 respectively. Relatively high values of maximum hydraulic velocity and maximum rate of seepage were generally observed. These were expected considering the soil classification and the particle size distribution results. The minimum and maximum values of hydraulic velocity of 2.92E-04 and 4.15E-04 m/sec were observed respectively at TP1 and TP4 for the numerical method using SEEP/W. As for the analytical method, minimum and maximum values of hydraulic velocity of 1.29E-04 and 1.5E-03 m/sec were observed respectively at TP2 and TP3.

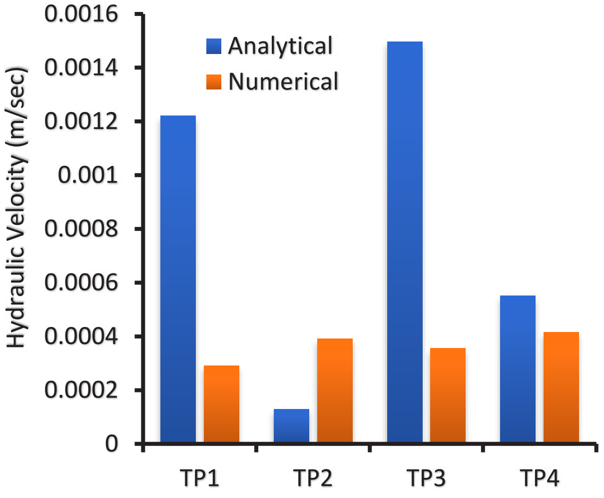

Figure 3: Hydraulic velocity analysis results

For the maximum flux across the centre of the dam, the minimum and maximum values of rate of seepage of 8.64E-05 and 1.27E-04 m^3/sec were observed respectively at TP2 and TP1 for the numerical method using SEEP/W. As for the analytical method, minimum and maximum values of rate of seepage of 1.49E-05 and 1.73E-04 m^3/sec were observed respectively at TP2 and TP3. The values of the maximum hydraulic velocity and maximum flux results are indications of need for sufficient and well monitored compaction and careful selection of core material with a very low permeability for adequate design against piping failure. Such core materials are mostly inactive clay soils.

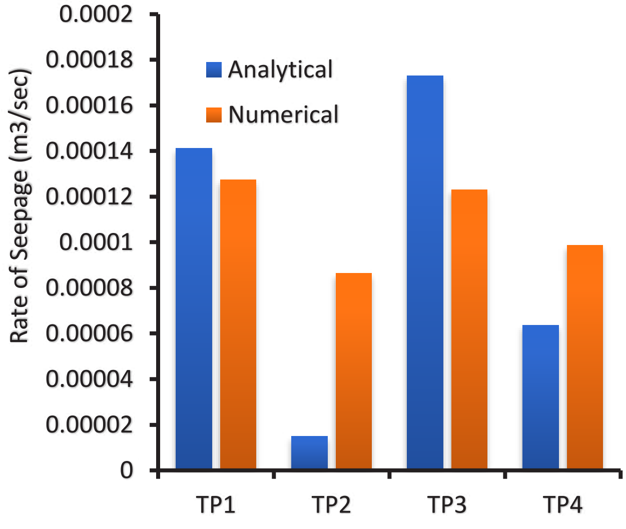

Figure 4: Rate of seepage analysis results

4 CONCLUSION

Based on the slope stability and seepage analyses conducted on the dam, the following conclusions were drawn:

a) The safety factor results show that the embankment is safe from slope failure having a minimum safety factor value of 2.302 at TP1. Results of TP2 – TP4 have higher safety factor values.

b) A minimum safety factor result of 1.416 was observed at TP 1 after a worst case scenario of rapid drawdown from the maximum anticipated flood water height of 7.6 m to 0 m in 24 hours which is satisfactory, although a little short of the conventional value of 1.5.

c) The results of maximum hydraulic velocity and rate of seepage through a line around the middle of the embankment cross section of 4.15E-04 m/sec and 1.27E-04 m^3/sec respectively were indication of need for sufficient and well monitored compaction and careful selection of core material with a very low permeability for adequate design against piping failure.

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