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ON THE DYNAMIC MECHANISM OF EROSION PROCESS①

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ABSTRACT

Erosion process is controlled and affected by various forces of different nature. Erosion processes induced or affected by these forces can be classified into three categories: erosion process induced by endogenic agent, by exogenic agent and associated with human activities. In this article, various dynamic mechanisms are systematically reviewed. Effects of tectonic stress and gravitational stress fields on erosion, effects of human activity on erosion, effect of exogenic forces such as water and wind erosion are discussed respectively.

Key Words: Endogenic agent, Exogenic agent, Erosion process, Geomorphological evolution, Tectonic stress, Gravitational stress.

I. INTRODUCTION

Erosion is an important phenomenon in the geomorphological evolution. It is controlled and affected by various forces. According to the nature, these processes can be classified into two categories: process induced by natural forces and by human activities. Natural forces can be subdivided into endogenic forces and exogenic forces. Endogenic forces refer to those from the

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interier of the crustal mantle. One of the most important symbol is the plate movement in the lithosphere which results in the formation of the global tectonic stress fields. Exogenic forces refer to those from the atomosphere and hydrosphere. Landforms remoulded in the geomorphological process are the result of the antagonism of the endogenic and exogenic forces (Scheidegger, 1979). But recent studies reveal that human activity, which has so long been a neglected factor on the evolution of landform (Ren, 1989, Xu and Ai, 1989), is also an important geological agent (Ren, 1989). Since erosion is a key link in the evolution of landform, research into erosion processes can not be separated from various forces of landform evolution. It is based on such an idea that the authors suggest to analyse systematically the erosion process with respect to the various forces.

II. EROSION INDUCED BY ENDOGENIC FORCES

The study on erosion problems is undoubtedly of great importance. But people used to pay more attention to exogenic forces, such as the effect of flowing water, wind and glacier, ... etc. while researches into endogenic forces are less, and effects of tectonic stress field and the gravitational stress field of rock—earth body are rarely involved. Geological factors such as rock property and its structure used to be paid much attention to, not as agent of erosion process, but rather as the results of agent, i.e , they were considered as important condition of erosion, as a boundary condition or an initial condition of erosion process.

Recently, more and more attention has been paying to endogenic forces and consequently, the induced erosion processes. As a geologico-geomorphological phenomenon, landslides used to be regarded as a result of exogenic forces of geological action, i.e., accumulation of mass, erosion or lubrication of groundwater can make side slopes unstable with the help of certain stimulating factor. But experiments performed in Vienna Technology University indicate that, landslides are affected and controlled to some degree by tectonic stress field. The displacement measurement of the slow movement of the Valley of Gastein in Austria reveals that the averaged sliding vector of the mass is parallel to one of the shearing surfaces computed from joints (Hauswirth and Scheidegger, 1980). Another study on the displacement of the Lesach Valley confirms that the direction of slide coincides with the major principal stress of neotectonic stress field (Hauswirth, Roch and Scheigegger, 1979). Research on the instant landslide at Sale Mount, Dongxiang County of Gansu Province also reveals that the tectonic stress field plays a dominent role (Zhang, 1983). Research into the landslide and debris flow in the Wudu area of Gansu Province indicates that the direction of the landslide can be compared with the shearing surface (N 164°E, strike 74°— 254°) in the stress field, i.e., the direction is roughly East—West. The average trends of debris flow gullies are perpendicular to the direction of the principal compressional stress in the neotectonic stress field, N 33°E. (Scheidegger and Ai, 1987). Investigation into the subsided area in Ansai County of Shaanxi Province by Wu Chunlong et al (Wu, 1989) indicates that the dominent direction of subsided land accords with the conjugate shearing surfaces in the neotectonic stress field.

In addition to tectonic stress, gravitational stress is another important agent which affects erosion. In the Loess Plateau area, not only tectonic stress, but also the gravitational stress field of the rock–earth body that governs landslide, collapse, and debris slip, so they are called gravitational erosion. This is because prior to the occurrence of collapse it must have a specific landform condition—an exposed and projecting side slope. The existence of the exposed projecting slope releases most of the tectonic stress. But it is found that there exists residual stress inside the massif. The compound stress of gravitational and tectonic stresses used to be concentrated at the bottom of slope (Wuhan, 1984). So the existence of the gravitational stress enhances the effect of the tectonic stress field against stability of slopes.

Namely because of effects of the systematic endogenic forces, it renders the once random exogenic erosion process to show a tendency of selectivity. The joint plane and the river trends represent the direction of the major principal shear stress in the tectonic stress field and the fractured zone is more easily to be eroded and weathered. According to Chen Yongzong et al (Chen, 1988), the intensively and violently eroded areas in the Loess Plateau are mainly distributed on either sides along the valley of the Yellow River which stretches from north to south between Shanxi and Shaanxi Provinces. The major axis of the geometry of this severely eroded area is almost in the direction of North–South (Fig. 1). In order to expound the relationship between erosion and tectonic stress field in this area, maps with a scale of 1:100,0000 covering an area of E 108.6°– 111.7° and N 35.6°– 39° are used to analyse the density distribution of river system. There are 912 lines indicating the total length of the rivers of 9,232 km in the area. A rose diagram by counting the number of river trends at an interval of 10°(0 – 180°) is worked out (Fig 2). After calculating the data of the measured 912 lines representing the river system in the area (Yu, Jiang and Ai, 1985), the dominent directions of the river system are found to be 137°, and 73°. Therefore, the principal compressional stress in the neotectonic stress field in this area is N 100.5°E. That is almost the East–West direction. This direction basically coinsides with the direction of compression induced by the movement of the Pacific Plate against the North China (Ai, 1987). Thus, it is proved that the conclusion drawn by deducing the neotectonic stress field from circumstances of river system in this area is believable.

Recent studies (Ai, Lu and Wang, 1986, Lu, Ai and Zen, 1989) also show that sections which are perpendicular to the direction of principal compressional stress have much higher value of concentration of stress than other areas. The great fracture zone on the Yellow River Valley which indicates the violent tectonic movement of meridianal direction runs from North to South through the extremely eroded areas shown on Fig. 1, is just perpendicular to the East–West direction of the principal compressional stress. So the rocks are extremely fractured and intensive erosion is more easily developed in this area.

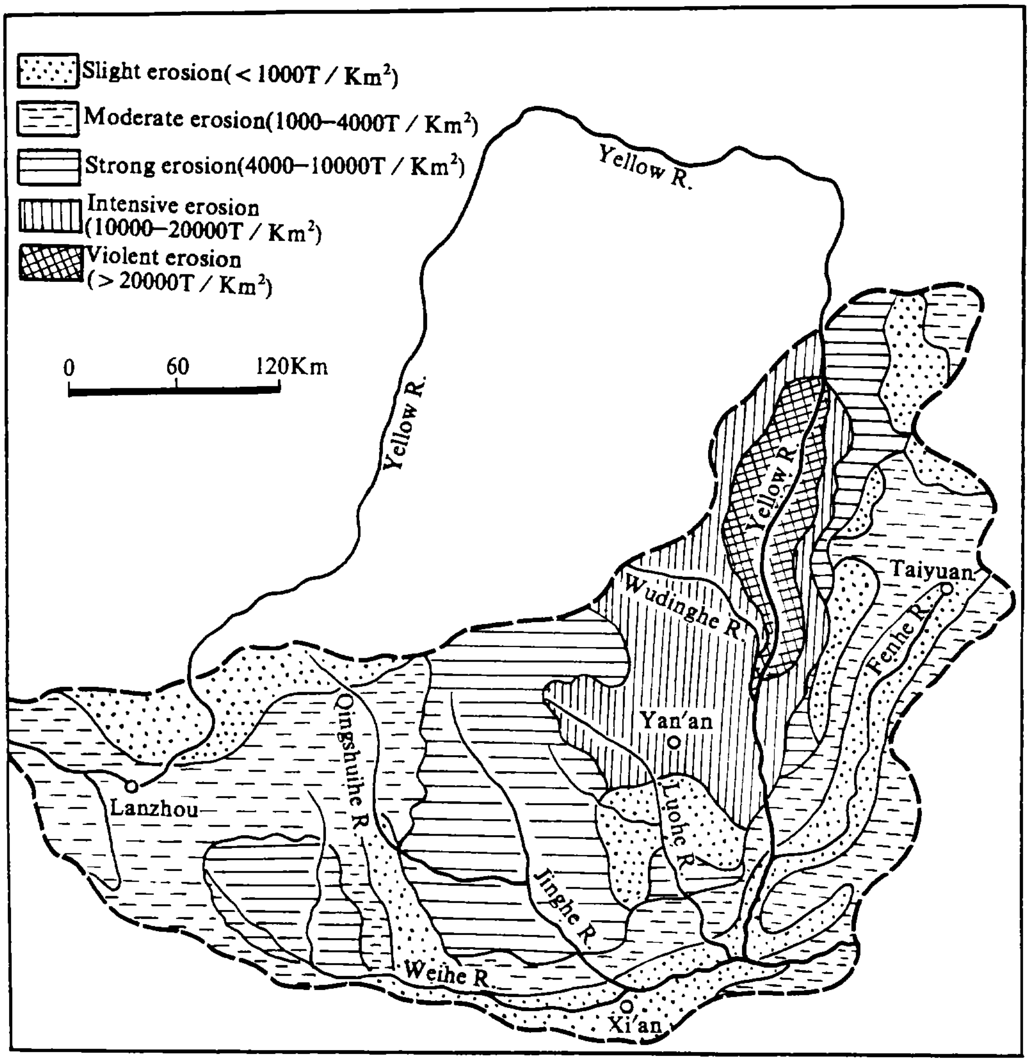

Fig. 1 Regionalization of intensity of erosion in the Loess plateau (after Chen, 1988)

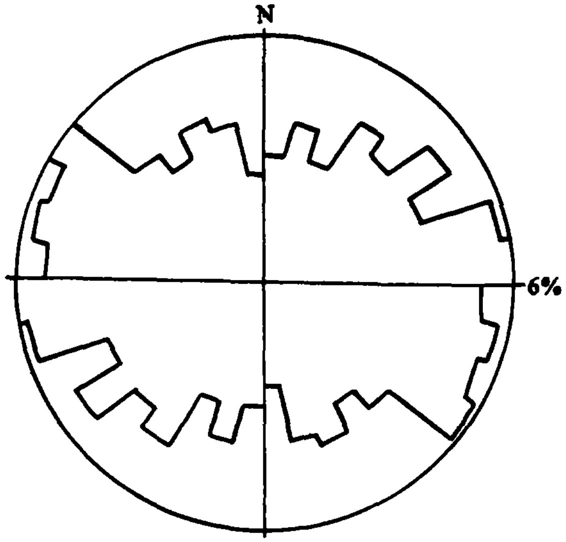

Fig. 2 The rose diagram of the river system

III. EROSION CAUSED BY EXOGENIC FORCES

Exogenic forces are the most active agent and directly participate in the erosion process. Exogenic forces function to implement or to participate in the transportation of substances on the surface of the earth. They are also active stimulating factors to collapses and landslides. Therefore exogenic forces have been paid more attention in studies on erosion. There are lots of research results in this field, because of the limited length of the article, only water erosion and wind erosion are briefed as follows.

Considering the present status of studies on water erosion, it can roughly be divided into two approaches. One is to work out empirical relationship among the quantity of erosion, precipitation factor and other factors using statistics, such as the most widely used Universal Soil Loss Equation,

$$A = RKLSCP \tag{1}$$

where A is the average annual soil loss from a specific field (kg/m^2); R is the erosion index related to rainfall intensity; K is soil erodibility factor; L is length of slope; S is gradient factor; C is cropping management factor; P is supporting conservation practice factor. Although some scholars (Mu and Meng, 1986) pointed out that there are shortcomings in this equation, for example, the rainfall factor can not be simply multiplied by the other factor, it is still widely used in many countries in the world. Another example is the statistical model set up by a

Chinese scholar, Jiang Zhongshan (Jiang, 1989). The model is mainly developed for splash erosion by raindrops on slopes, using the data of Ansai Experimental Station.

For the case of splash erosion on the upward side of the slope:

$$S_u = [0.562 - 0.3652J / (2.6238 + 0.0378J)](EI_{30})^{0.736} \quad (2)$$

For the case of splash erosion on the downward side of the slope:

$$S_d = [0.520 + 0.040J - 0.00076J^2](EI_{30})^{0.769} \quad (3)$$

Where S_u and S_d are amount of splash erosion up and down along the slope, J is gradient; EI_{30} is rainfall index for soil erosion.

Another approach is to develop models, based on certain physical background, such as the slope evolution equation developed by Culling (Culling, 1963).

$$\frac{\partial H}{\partial t} = \alpha\frac{\partial^2 H}{\partial x^2} + \beta\frac{\partial^2 H}{\partial y^2} \quad (4)$$

where H(x,y,t) represents the height of the point (x,y) on a horizontal plane (x,y) at time t. It represents a geomorphological curved surface. Another example may serve the work of Zhang Dexuan of Lanzhou University, who, based on the research of predecessors, applies relevant theories of hydraulics and hydrology in establishing a mathematical model for the case of water erosion in the Loess area (Research thesis of Zhang Dexuan):

$$Q = KL^m \sin^n\theta \quad (5)$$

where Q is rate of sediment discharge, L is slope length, θ is gradient and K, m, n are coefficients of factors related to rainfall intensity, roughness of the slope, the specific gravity and sediment diameter, and vegetation covering.

Wind erosion often takes place in loose sandy areas, which occupies a considerable proportion on the Loess Plateau. The main factors that affect wind erosion are wind velocity and the ground surface condition. Some empirical relationships between wind velocity and wind–borne sediment discharge under different surface conditions are listed in Table 1. (Research Team of Wind Erosion Problems in Shengfu–Dongshen Coal Field, 1988)

Table 1 Empirical equations of wind velocity and wind–borne sediment discharge under different surface conditions

Surface conditions	Empirical equations	Remarks
Moving dunes and sandy land	$Q_1 = 0.407373 \times 1.645^{V}$	In the equations: V is wind velocity (m / s) and Q is wind–borne sediment discharge (g / cm / min)
Semi–moving sandy land	$Q_2 = 0.86355 \times V^{7.2378} \times 10^{-7}$	
Semi–fixed sandy land	$Q_3 = 6.1105 \times 10^{-6} \times V^{4.8}$	
Fixed dunes and sandy land	$Q_4 = 1.16477 \times 10^{4} \times V^{0.59492}$	
Wind–eroded land on bedrock	$Q_5 = 8.59246 \times 10^{-5} \times V^{1.45929}$	
Sandy loess	$Q_6 = 1.2257 \times 10^{-2} \times e^{0.50625v}$	

Besides water erosion and wind erosion, glacier effects and freeze–and–thaw action are also exogenic forces in the erosion process. It should be pointed out that exogenic forces are random, but endogenic forces are deterministic and systematic. Because of the existance of the systematic endogenic forces, erosion at different places often shows certain tendency of selectivity that gives rise to the big difference in the intensity of soil erosion.

IV. EFFECT OF HUMAN ACTIVITIES ON EROSION

Human activity is an important agent applied to natural condition. With the rapid population growth and the intensified human activities, human beings are exerting more and more effects on the environment. The environmental landscape which people see today is almost more or less the reformed one that has been affected by human activity, except in few rare cases. Geomorphological evolution processes, both erosion and aggradation processes, are affected by human activity directly or indirectly. As far as some large–scale coastal landforms are concerned, they are also considered as the result of human activity, so they are called coastal landform (Ren, 1989). Moreover, recent studies (Wang, Wu and Niu, 1989, Fan, Yang and Ai, 1989, Wang, 1989) reveal that the advance or retreat of desert and the change of lakes into arid areas are all related to human activities. Appropriate production activity can lead to deserts retreat and even turn it into oases, while improper human activity can intensify the desertification and threaten the productivity and human life. Rational human acitivity can make use of lake resources for the benefits of human society, while the excessive exploitation may result in the accelerated disappearance of lakes, disqualification of water quality, and deterioration of environment.

Erosion process is the essential link in geomorphological evolution. It is undoubtedly affected by human activity as a specific geological agent. In fact, human production activities, such as cultivation, reclamation, grazing, urbanization, mining and construction of roads ... etc., all affect erosion process directly or indirectly. As far as the soil conservation measures are concerned, they are aimed to prevent or slow down the erosion process so that man's production and life are not to be threatened. It should be emphasized that human activity is a geological agent of specific nature, it differs from endogenic and exogenic forces which participate in and basically control the occurrence of erosion, human acitivity can not control nor change the erosion process induced by endogenic forces, but it may exert certain influence to mitigate or intensify the erosion process. For example, degradation process can be changed into aggradation process by water conservancy or conservation measures. Since we can make sure that human activities may affect or change to some degree the erosion process caused by exogenic forces, a series of conservation measures and desertification–resistant measures are adopted. The quantitative evaluation of effects of human activities on erosion is an important topic in the study on erosion. Mathematical models dealing with effects of human activities on water erosion and desertification have been developed (Xu and Ai, 1988 a, b, Fan, Yang and Ai, 1989). In fact, the effect of human activity on erosion (including water erosion, wind erosion, glacier erosion and freeze–and–thaw erosion) can be described by a generalized mathematical model. From the point of view of system analysis, any erosion process can be regarded as a process in which a group of natural input factors turn into output results. In this process, the effect of human activity is to modify the input–output relationship, and thus increases or decreases the output. This process can be described schematically in Fig. 3.

In Fig. 3, $x_1, x_2, \ldots\ldots x_n$ represent a group of natural input factors, they are functions of time t; Y represents the output; M represents the degree of influence affected by human acitivity.

The erosion process described above may be written as:

$$Y = M\, f(x_1, x_2, \ldots\ldots x_n) \tag{6}$$

Take derivative of Y with respect to time t, we obtain:

$$\frac{dY}{dt}=\frac{dM}{dt}f(x_1,x_2,\ldots\ldots,x_n)+\sum_{i=1}^{n}\frac{\partial Y}{\partial x_i}\cdot\frac{dx_i}{dt}$$

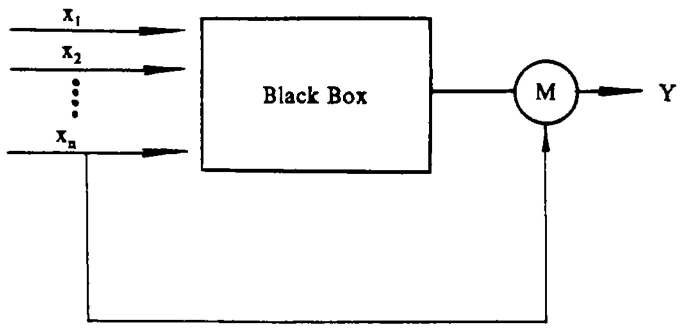

Fig. 3 Schematic diagram of input—output relationship for erosion process

Divide both sides of the equation by Y, and let coefficient $\alpha_i=\frac{\partial Y}{\partial x_i}\cdot\frac{x_i}{Y}$ (i = 1,2, ... n) be an elastic coefficient of input factor x_i (i = 1,2,...... n) to the output Y, we come to:

$$\frac{dY}{dt}/Y=\frac{dM}{dt}/M+\sum_{i=1}^{n}\alpha_i\left(\frac{dx_i}{dt}/x_i\right) \tag{7}$$

In order to facilitate the computation, Eq. (6) can be written as the finite difference equation

$$\frac{\triangle Y}{\triangle t}/Y=\frac{\triangle M}{\triangle t}/M+\sum_{i=1}^{n}\alpha_i\left(\frac{\triangle x_i}{\triangle t}/x_i\right)$$

Solving the equation, the time interval $\triangle T$ is taken as an identical value for all terms and $\triangle t\neq 0$, we get:

$$\triangle Y/Y=\triangle M/M+\sum_{i=1}^{n}\alpha_i(\triangle x_i/x_i) \tag{8}$$

Generally speaking, $\frac{\triangle x_i}{x_i}$(i = 1,2, ... n) and $\triangle Y / Y$ can be obtained from the observed data. As long as we can determine all the elastic coefficients α_i(i = 1,2, ... n), $\triangle M / M$, the rate of change in the degree of human activitity on erosion process, can be computed through eq. (8). Thus, the effect of human activity on erosion can be expressed by:

$$m = \frac{(\triangle M / M)}{(\triangle Y / Y)} \times 100\% \tag{9}$$

In analyzing practical problems, x_i(i= $1,2$, ... n) and Y may have different meanings. For example, in water erosion process, runoff can be regarded as the input, and sediment discharge the output. The erosion process caused by rainfall can be divided into two processes, the runoff formation process and the sediment yield process. In the runoff formation process, precipitation can be regarded as the input and runoff the output. While in the sediment yield process, the runoff can be regarded as the input and sediment yield the output. In wind erosion process, wind velocity can be considered as the input and wind–borne sediment load the output. The degree of influence affected by human activity M is a dimensionless value for reference within a certain time period of erosion process. If the initial value is defined as 1, the values of M at any time later may be obtained by comparing with 1.

All the elastic coefficients are synthetic indices, related to landform, soil component, vegetation covering, and rainfall and wind characteristics etc. These coefficients can be obtained indirectly by other methods.

Application of above–mentioned model has already been reported in some published papers (Fan, Yang and Ai, 1989, Xu and Ai, 1988 a, b).

V. CONCLUSION

The dynamic mechanisms of the erosion process are of great importance in the study on erosion problems. Endogenic force, exogenic force and human activity are the three main agents in the erosion processes. Tectonic stress and gravitational stress fields contribute not only to gravitational erosion such as collapse, landslide and debris slip, but also affect and control water erosion, wind erosion, glacier erosion and freeze–and–thaw erosion as well. Erosion caused by exogenic force mainly refers to water erosion and wind erosion, but other erosional modes or types should not be neglected. Being controlled and affected by endogenic forces, erosion process caused by exogenic forces shows some tendency of selectivity. Human activity is a specific geological agent, and it's effect on erosion has become a public concern all over the world. Study on this problem becomes main content of contemporary man–earth relationship.

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