Benggang erosion in sub-tropical granite weathering crust geo-ecosystems: an example from Guangdong Province

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Abstract Within a theoretical framework of geo-ecology, this paper deals with benggang erosion processes in areas of China with a sub-tropical climate and a granite weathering crust. Benggang erosion and its associated erosional morphology occur as the result of the reverse succession of vegetation induced by man's destruction of the forest. In this study, a threshold model for the initiation of benggang has been generalized into five stages, and relationships between benggang density and forest and population factors have also been established.

INTRODUCTION

Guangdong Province, China, is located in the humid tropical and southern sub-tropical zones with a mean annual precipitation of 1500-2000 mm. Granites are widely distributed and covered by a well-developed weathering crust. Under natural conditions, the hillslopes are covered by a dense evergreen broadleaf forest, which protects soils from water erosion, in spite of a high rainfall erosivity. As soon as the vegetation cover is destroyed by man, however, the balance between high erosion resistance and high erosivity in the geo-ecosystem will be upset, leading to a sharp decline in the ratio of resistance to erosivity and therefore a high rate of sediment transport by water. "Benggang" is the erosional morphology resulting from this high-intensity erosion.

"Benggang" is a Chinese word, meaning "a collapsing hill". There is no equivalent word in English. In this paper, benggang is defined as a severe erosional morphology, with a very high intensity of sediment transfer, formed by the joint operation of mass wasting and water erosion, with the former being dominant. On the basis of field observations and measurements from Guangdong Province, this study deals with benggang erosion from a geo-ecological viewpoint.

BENGGANG INITIATION IN RESPONSE TO THE REVERSE SUCCESSION OF VEGETATION

With a river basin as its functional unit, the drainage basin geo-ecosystem comprises natural factors such as climate, geology, topography, vegetation, hydrology and soils as well as human activity in the basin. The fundamental processes in a geo-ecosystem are primarily the hydrological cycle and the bio-geochemical cycle, and it can therefore be divided into two sub-systems, namely, the drainage basin hydro-geomorphological sub-system and the vegetation-ecological sub-system. The two sub-systems reflect the material and energy fluxes at the lithosphere-biosphere interface and their transmission and transformation processes in different ways.

The transfer of sediment, dissolved matter and nutrients in association with the water cycle directly affect the characteristics of soils, and in this way the growth of vegetation may be influenced. Equally, vegetation can effectively influence soil erosion, and it also plays an important role in nutrient cycling in soils. Thus, a change in vegetation would exert an influence on hillslope runoff generation, soil erosion and nutrient migration, leading to a further change in the hydro-geomorphological sub-system. A close coupling between the vegetation-ecological sub-system and the hydro-geomorphological sub-system therefore exists.

The climax vegetation community in humid tropical and subtropical southern China is evergreen broad leaf forest, which has a very high primary productivity and a high-intensity nutrient cycle. However, due to the very strong leaching caused by high temperatures and high precipitation, the P, Ca and organic N contents of soils are rather low. In such ecosystems, the maintenance of a high primary productivity is related to the fact that the litter and plants decompose rapidly and the resultant nutrients enter the cycle immediately. The destruction of forest by man disrupts the closed cycle of mineral elements in such an ecosystem, and leads to an intensive loss of these elements during high-intensity rainfall. Ultimately, these elements will be transported out of the drainage basin by flowing water. Hence the remaining nutrients will be insufficient to support the high-intensity nutrient cycle of an evergreen broadleaf forest. In the secondary succession nutrient deficiency-tolerant tree species such as Masson pines (*Pinus massoniana*) will take over and the vegetation will deteriorate into a mixed conifer and broadleaf forest or even a conifer forest, usually dominated by Masson pines. If the secondary forest is subsequently cut by man, the nutrient and soil losses will again increase, making the vegetation deteriorate further into tropical shrubs, steppe or even a totally barren tropical desert. This process of reverse succession of vegetation is caused by man's repeated destruction of vegetation in the study area.

The reverse succession of vegetation is associated with a sharp decline in vegetation biomass. Because quantitative historical data are not available, the variation of vegetation biomass during the reverse succession sequence can only

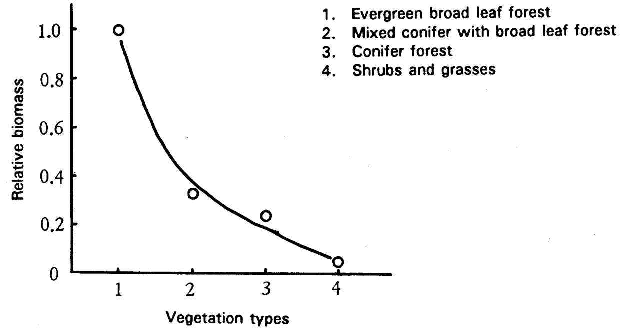

Fig. 1 Comparison of biomass per unit area for different vegetation types, with evergreen broadleaf forest assumed as 1; based on data from the Tiechanghe River basin, Guangdong Province (Department of Geography, Zhongshan University, 1987).

be approximated by a comparison of the biomass of different vegetation types currently represented in the study area, using space-time substitution (Fig. 1). Based on Fig. 1 it can be seen that the vegetation biomass decreases rapidly during the process of reverse succession, resulting in a decline in vegetation cover and in its effectiveness to resist erosion. As a result, hillslope erosion is intensified, from sheet and rill erosion to severe gully erosion. With the loss of vegetation cover, soil moisture in the red earth granite weathering crust exhibits a much larger seasonal variation than before, and deep cracks result from the marked wet-dry cycles in the soils. During periods of rain, water flows into the cracks, substantially reducing the shear resistance f_0. At the same time, an increase in gully depth produces a larger driving force f_1 acting on the soil blocks dissected by the cracks (Fig. 2(a)). Thus the risk of slope failure is greatly increased. When the gully is cut to a critical depth, shallow slips and slides will occur with the initiation of a benggang. This can be described by a threshold model modified from Statham (1977).

The ratio f_0/f_1 is termed the safety factor. The lower this factor, the greater the likelihood of slope failure. On average the occurrence of failures is related to the condition $f_0/f_1 = 1$. The temporal variations in f_0/f_1 before vegetation destruction is illustrated in Fig. 2(b), showing that f_0/f_1 is considerably higher than 1 and the long-term average does not change significantly with time. The saw-toothed fluctuations superimposed on the trend line represent the seasonal variation, and the short verticals represent the influence of rare events with different magnitudes such as typhoon-induced high-intensity rainstorms. When the vertical crosses the threshold line $f_0/f_1 =$ 1, failure will occur, but its frequency is very low.

Figure 2(c) shows how the safety factor declines with the reverse succession of vegetation. This is caused by a decreasing f_0 and an increasing f_1 (see Fig. 2(a)). The saw-toothed fluctuations and short verticals have the same meaning as in Fig. 2(b). When they reach the threshold line $f_0/f_1 = 1$, a

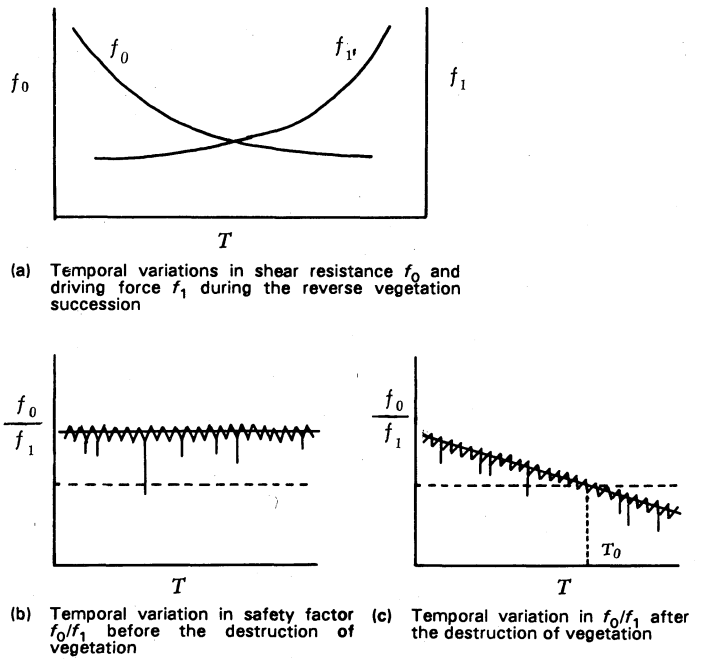

Fig. 2 Description of the model showing the threshold for the initiation of a benggang.

failure will possibly occur. However, in cases where the trend line intersects the threshold line, a slope failure will inevitably occur. This can be regarded as the starting point of benggang development, as represented by the time T_0 in Fig. 2(c). Before the occurrence of active mass wasting, the erosional process may be considered to be at a pre-benggang stage.

The foregoing discussion demonstrates that the initiation of a benggang can be regarded as a catastrophic process, which occurs after a threshold has been crossed. The stage with limited sheet erosion before vegetation destruction, the stage with increasingly intense gully erosion after vegetation destruction, and the stage with high intensity benggang erosion caused by the joint operation of mass wasting and flowing water transport after a complete destruction of the vegetation, can be related to the three different states of the geo-ecosystem in the sub-tropical granite areas of southern China that are undergoing a reverse vegetation succession induced by man's repeated destruction of vegetation. This indicates that the different states of the geo-ecosystem reflect differences both in erosional processes and erosion rates.

BENGGANG EVOLUTION

Existing studies indicate that the development of a benggang demonstrates similarities to the cycle of landscape evolution proposed by Davis (1899), and reflects stages of youth, maturity and old age. In this investigation the development of a benggang has been generalized using a five-stage descriptive model as follows:

(a) *Initiation stage:* Starts with the frequent occurrence of mass wasting after the reduction in slope stability. The mass-wasted materials are rapidly removed by runoff, and the slope stability is again reduced. Slumps and slides again occur. The erosion rate is not very high, but it increases markedly.

(b) *Stage with rapidly increasing erosion:* The erosional rate increases very rapidly, and the benggang enlarges both headward and laterally. At this stage the erosion rate reaches a maximum.

(c) *Stage with gradually declining erosion:* The retreat of the benggang's collapsing walls slows down, with a much lower rate of sediment transfer. The morphology of the benggang tends to be gradually stabilized.

(d) *Stable stage:* The erosion rate further declines and the frequency of occurrence of slumps, slides and falls becomes very low. Deposition of mass-wasted materials at the base of the walls produces a gentler slope. The cone formed by the mass-wasted material with an increasingly gentle slope is gradually vegetated, further reducing the erosion rate.

(e) *Final stage:* Vegetation in the benggang becomes denser, and the walls no longer collapse and even become vegetated. Vegetation intercepts the sediment transported from the upper slope and deposition occurs within the benggang. Finally, erosion becomes negligible, and the benggang may be replaced by a non-benggang landform.

Based on data from Wuhua County, Guangdong Province, the average erosion rates for benggangs at these different stages are shown in Fig. 3. Based on space-time substitution, the curve in this figure may approximate the changing erosion rate of a benggang during its development.

The five stages of benggang development outlined above are determined by the interrelationships and interactions between the system's components, with positive and negative feedback playing a controlling role. The increasing erosion rate is controlled by a positive feedback, while the declining erosion rate reflects negative feedback.

After the initiation of a benggang, the area of its upper catchment

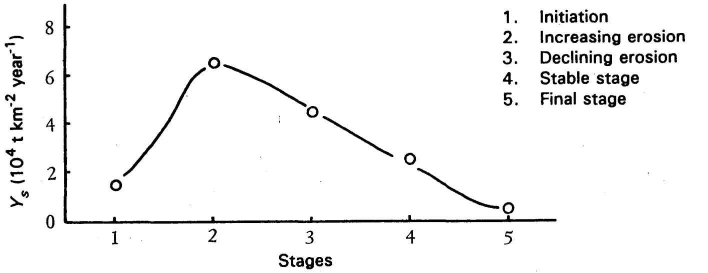

Fig. 3 Erosion rate Y_s of a benggang at different stages of development.

increases with the lateral enlargement of the benggang, leading to increased runoff which can remove products of mass-wasting more rapidly and therefore enhances the erosion of the benggang. As a result, the upper catchment of the benggang can be further increased. However, when its growth reaches a certain point, an inverse trend will occur, since the benggang will gradually approach the upper divides of the catchment and runoff will be reduced. If the benggang develops on a laterally concave hillslope or hollow, the lateral enlargement of the benggang will also reduce the upper catchment area, as shown in Fig. 4(a). All these produce a reduction in the runoff entering the benggang from the upper and lateral parts of the catchment (Fig. 4(b)).

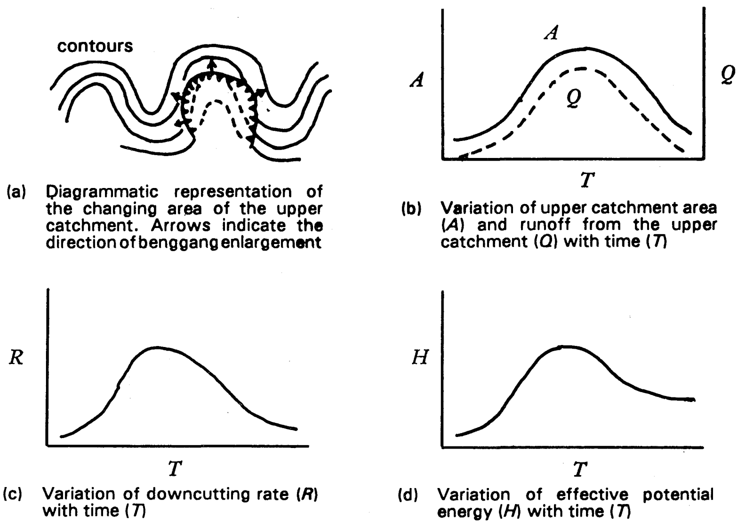

Fig. 4 Temporal variation of controlling variables during the development of a benggang.

During the stage with increased erosion, the downcutting of the channel in the benggang caused by the increasing runoff, will increase both the rate of downcutting of the benggang and its topographical potential energy expressed as the height difference between the top of the headwall and the channel outlet. However, when the downcutting proceeds further, the weathered layer may be cut through; or, when the weathering front is approached, more and more coarse debris will be left to form an armour layer. Both would slow down or even stop the downcutting of the benggang, and the effective potential energy of the benggang will no longer increase (Figs 4(c) and (d)). When the upper or lateral divides are reached by the enlarging benggang, the resultant reduction in total height difference will decrease the effective potential energy. As a result, the benggang will enter the stage with declining erosion. When the upper catchment area becomes too small to provide the benggang with appreciable runoff and the effective potential energy begins to decrease, the benggang enters the stable stage and ultimately the final stage. After undergoing a complete cycle of benggang erosion, the hillslope attains stability. This is associated with the recovery of dense vegetation and sediment accumulation within the benggang.

The development of a benggang starts with the destruction of forest by man, and ends with the recovery of the vegetation. By considering the coupling of the hydro-geomorphological sub-system to the vegetation-ecological sub-system in the drainage basin geo-ecosystem, a better understanding of benggang erosion is obtained, and on this basis control measures based on vegetation can provide a effective tool for controlling benggang erosion. The introduction of control measures based on vegetation will greatly speed up the development of the benggangs towards the stage with declining erosion and the stable or final stage.

Investigations have shown that a stable benggang may sometimes be rejuvenated. If an extreme rainstorm event occurs, the flowing water may be able to breach the pre-existing armour layer. Erosion may then be intensified, with the benggang reverting to the stage with increasing erosion. If other conditions are favourable, a long duration, low intensity rainfall event may also cause the rejuvenation of a stable benggang. When the material in the stable benggang has been fully wetted and the liquid limit is reached, an earthflow may occur, generating a further period of intense erosion.

THE RELATIONSHIP BETWEEN BENGGANG EROSION AND VEGETATION AND HUMAN ACTIVITY

As indicated above, benggangs result from the reverse succession of vegetation. Studies have indicated that most of the benggangs in Guangdong Province are less than 150 years old. In general they are only 70-80 years old (Zeng, 1991). This is broadly coincident with the history of man's destruction of the evergreen broadleaf forests in this region, indicating a cause-effect relationship. Due to the lack of data, it is very difficult to reconstruct the timing of benggang development in relation to the reverse vegetation succession initiated by man. We are, nevertheless, able to demonstrate the influence of vegetation and human activity on benggang erosion by comparing the spatial distribution of the benggangs with the distributions of the influencing factors.

In this study we have used an index of benggang density D_b, defined as the number of benggangs per unit area within a given area to express the intensity of benggang erosion in an area. D_b can be used to reflect the frequency of occurrence of benggangs in space. Based on data from Wuhua County, Guangdong Province, benggang density D_b has been plotted against forest cover (Fig. 5(a)). Although the points exhibit considerably scatter, a clear inverse trend is still evident, i.e. the greater the forest cover, the lower the benggang density.

Since mankind appeared on the earth, human activity has played an

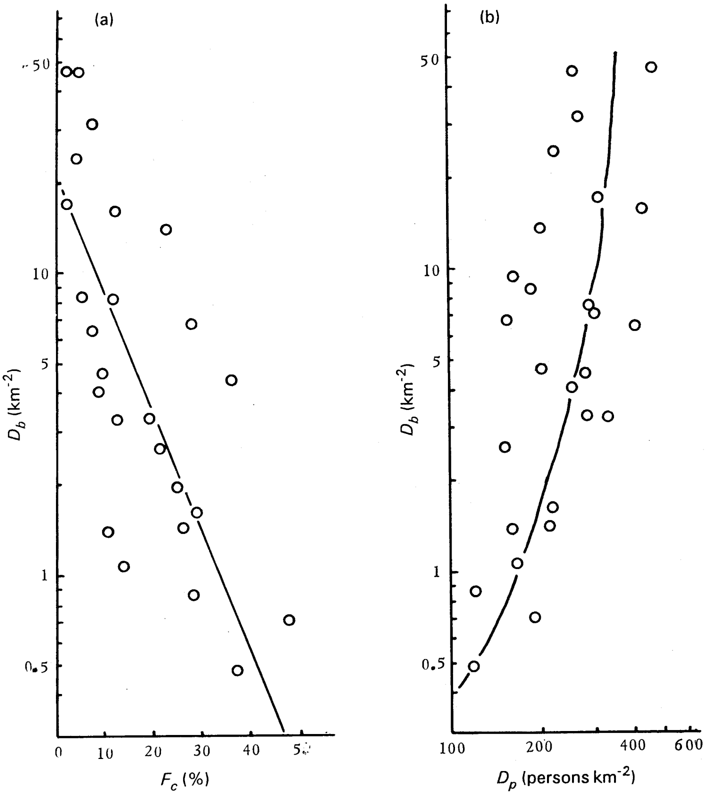

Fig. 5 The relationship between (a) benggang density D_b and forest cover F_c, and (b) benggang density D_b and population density D_p.

increasingly important role in geo-ecosystems. In effect, the vegetation distribution in southern China resulted from man's destruction; the greater the human activity, the greater the extent to which the forest has been destroyed by man. Furthermore, other human activities such as cutting into hillslopes for road- and house-building and for quarrying building materials, may cause the loss of sideslope stability when the threshold condition is approached. The overall intensity of human activity can be approximated by population density (D_p). Based on data from Wuhua County, the relationship of D_b to D_p is presented in Fig. 5(b), indicating a sharp increase in D_b with D_p. The curve is concave-upward, indicating that the population factor is an important control on the occurrence of benggangs.

CONCLUSIONS

A benggang is an erosional landform with a very high intensity of sediment transfer, formed by both mass wasting and water erosion, with the former being dominant. The sediment yield of a single benggang at its maximum is of the order of 80 000 t km^{-2} $year^{-1}$ in Wuhua County, and up to 391 000 t km^{-2} $year^{-1}$ in Deqing County, Guangdong Province (Wu *et al.*, 1989). Benggang erosion is thus the erosional process with the highest erosion rates in China.

Benggang erosion occurs as a result of the reverse vegetation succession induced by man's destruction of vegetation in the study area. The initiation of a benggang can be described by a threshold model. From the viewpoint of geo-ecology, different erosional processes are related to different states of the geo-ecosystem which is strongly influenced by man. A cycle of benggang erosion has been proposed in this study. This is composed of five stages. The transition from one stage to the next is controlled by positive and negative feedbacks within the system.

Benggang density is closely related to both the extent of forest cover and population density; the lower the forest cover or the higher the population density, the greater the benggang density. Inappropriate human activities are the most important factor responsible for the occurrence of benggang erosion. Amongst these activities, the most important is man's destruction of the forests.

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