A Geomorphic Approach for the Design of Drainage Systems on Reclaimed Mine Areas

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Abstract

Effective drainage systems are required for reclamation of mine-disturbed areas to control surface water runoff and avoid excessive erosion. For the conventional structural design approach, armouring material necessary to satisfy the design criteria should not move during the design flood event since displacement would uncover the erodible underlying materials. This paper discusses an alternative geomorphic approach for designing drainage channels and watershed landscape. The approach is based on quantitative studies of geomorphic processes operating in a watershed. A design based on the geomorphic approach replicates the configuration, channel regime, sediment volume and hydrology of natural and mature drainage systems. Movement of some armouring material is acceptable in such an approach because the channels are allowed to mature by natural degradation and aggradation, with erosion rates comparable to the natural environment. The key advantages of a geomorphic approach over a purely structural approach include reduced sizes of armouring material, geomorphologically sustainable landscapes, "walk-away" or maintenance-free design and reduced liability in the future. The geomorphic approach is illustrated using the example of a coal mining operation in northwest U.S.A. The paper discusses field data collection, design criteria, typical design details, and construction methods.

Introduction

Mine closures and reclamation of disturbed areas involve the re-creation of sustainable landscapes where the local hydrologic systems have been altered. One key component of a mine closure plan is the development of an effective drainage system capable of controlling surface water runoff and avoiding excessive erosion. There are two design approaches, not necessarily mutually exclusive, that can be adopted for this purpose. One is the conventional structural design approach to erosion and sediment control. An alternative is based on a geomorphic approach that emulates the characteristics of natural drainage systems. This paper discusses the geomorphic approach for designing drainage channels and watershed landscapes.

Structural Design Approach

In the conventional structural design approach, runoff from the reclaimed areas is conveyed by a system of diversions, which may include gradient terraces, and secondary and primary rock-lined channels discharging into sedimentation ponds. Any armouring material for the drainage channels that are necessary to satisfy standard design criteria should not move during the design flood event since displacement would uncover the erodible underlying materials. This approach often produces rigid, non-erodible drainage facilities, which are designed to handle specific extreme flood events. This results in a predictable probability of failure and uniformity of design and construction, but does not necessarily achieve long-term sustainability. Constructed channels based on these methods may fail catastrophically because exceedence of the design event causes overtopping, washout of erosion protection, or channel degradation. Such failure is unacceptable because it often leads to accelerated and progressive erosion, channel relocation, high sediment yields and loss of aquatic habitat. A major deficiency of conventional methods is the absence of mechanisms for 'self-healing' of channels eroded after an extreme event.

Geomorphic Design Approach

Instead of using rigid systems that are designed for specific extreme events, the geomorphic approach offers a dynamic system capable of accommodating evolutionary changes without accelerated erosion or unacceptable environmental impacts. A design based on the geomorphic approach attempts to replicate the drainage configuration, channel regime, sediment volume and hydrology of natural and mature drainage systems. In the geomorphic approach, the drainage systems can be subject to periodic changes, but without the occurrence of accelerated erosion characteristic of many constructed systems. Movement of some armouring material is acceptable in such an approach because the channels are allowed to mature by natural degradation and aggradation, with erosion rates comparable to the natural environment. The maturing process is often characterized by changes such as channel migration, degradation, and aggradation. Anticipation of such changes to the closure reclamation drainage system allows the designer to incorporate geomorphic characteristics representing mature conditions. It also enables the designer to develop robust drainage systems with multiple lines of defence to accommodate the anticipated changes.

Characteristics of Natural Drainage Systems

Natural drainage systems are subject to gradual evolution and periodic erosion, which serves to enhance aquatic habitat and physical sustainability. Stream sizes and slopes are in dynamic equilibrium with drainage areas and lengths of overland flow paths. Natural stream systems are also equipped with several lines of defence and a robust self-healing capability. The essential characteristics of many natural and mature drainage systems are:

- Robust "self-healing" capacity provided by several "lines of defence" against sustained erosion
- Ready supply of armouring material where erosion has taken place
- Adjustment of channel shape and size to handle peak flows
- Gradual evolution
- Sediment balance
- Stable configuration (in regime) that is not vulnerable to rapid changes

Geomorphic Design Methodology

The geomorphic design methodology is based on quantitative studies of geomorphic processes operating in a watershed (Strahler 1964). Quantitative studies of geomorphic processes, particularly, erosion and sediment transport processes, have shown that geomorphic processes are controlled by stream and watershed parameters such as:

- dominant discharge
- stream order
- stream slope
- stream length
- surface water flow path length
- watershed area
- watershed slope
- sediment inputs
- sediment size distribution
- stream bank material composition

These characteristics, often overlooked in conventional structural design methods, can be built into reclamation drainage systems by design. The geomorphic parameters applicable to proposed reclaimed areas must be determined from an extensive field survey.

Example Geomorphic Characteristics

Recent work carried out at a proposed mine reclamation site in northwest United States provides a basis for illustrating the application of the geomorphic approach. Key observations during a field survey of natural drainage systems in the vicinity of the mine were as follows:

- The drainage areas of basins surveyed ranged from 0.4 to 8 ha.
- Stream type, size and slope were related to drainage area and length of overland flow path.
- The slopes of 1st order streams ranged from 5% to 60%.
- Vegetated waterways occur in basins with drainage areas less than 2 ha.
- The bottom widths of vegetated waterways ranged from 0.6 to 5 m.
- Basins with drainage areas greater than 2 ha support alluvial streams.
- Streams with slopes greater than about 20% have a gravel bed ($D_{50} \sim 3$ to 64 mm), while those with slopes less than about 20% generally have a silty bed ($D_{50} \sim 0.06$ mm).
- The bottom widths of alluvial streams were about 0.6 m.
- The maximum overland flow path length (i.e., overland distance until a channel is encountered) ranged from 75 to 300 m, depending on overland slope.

The geomorphic-based drainage systems for the proposed reclaimed areas were developed by considering the natural range of values for the above geomorphic parameters. These parameters are representative of a mature drainage system, where vegetation has already been well established. For a newly reclaimed area, when vegetation is just beginning to take hold, erosion protection normally available from mature vegetation is not available. Moreover, runoff rates from recently reclaimed areas tend to be much greater due to reduced infiltration rates, reduced moisture holding capacity of freshly disturbed soils and reduced evapotranspiration from areas with immature vegetation. During this transition period, which may take between three to ten years, various erosion protection measures will need to be implemented. For vegetated waterways, woody debris from land clearing, sacrificial armouring at selected locations and other measures will be required. For alluvial channels, armouring to suit conditions in the natural environment must be provided.

Design and Construction of Geomorphic Drainage Channels

The proposed reclaimed areas for the mine-disturbed areas were re-contoured to replicate a geomorphologically mature landscape. Figure 1 shows an example of the proposed re-contoured topography and drainage system for one section of the proposed reclamation areas. The top left corner of Figure 1 shows a drainage network designed using the structural approach. The uniformity of the structural design is a contrast to the more natural-like geomorphic design. The geomorphic drainage system consists of vegetated and alluvial channels.

In a geomorphic approach, estimates of peak flows in the various channels are only used to check for sizes of bed material that would have been required in a structural design approach and to verify similarity in flows with the natural analogues. The design storm selected for assessing the upper limit of bed material sizes was the 25-year, 24-hr rainfall event.

Vegetated Channels

Vegetation waterways are located in the upper portions of the drainage basins. Drainage areas associated with vegetated channels in the main drainage systems are less than the 2 ha observed in the field. The bed slopes of the designed vegetated channels range from about 12% to about 20%. This range of slope is within the range observed in the field for vegetated waterways. The drainage system was configured so that the maximum overland flow path length to any point on any of the designed vegetated waterways is within the field-observed range of 75 to 300 m. The lengths of the designed vegetated channels vary from 150 to 200 m, which are less than the lengths observed in the natural landscape.

Field observations indicate that natural vegetated channels are not protected by armour rock material. Rather, vegetated channels have a silty bed material. The lack of any obvious eroded sections in the mature vegetated channels surveyed suggests that these types of channels can carry significantly large flows under natural conditions. Armouring such channels is therefore unnecessary for long-term, post-transition periods after the constructed channel have developed a mature vegetated cover. However, some sacrificial armouring and temporary cover by debris are provided for the transition phase immediately following the reclamation and prior to development of a mature landscape.

Temporary erosion protection will be required during the transition period until vegetation stabilises these waterways. The following material was recommended to provide temporary erosion protection in the vegetated waterways:

- Woody debris (logs, roots, branches, etc., from clearing of land scheduled for mining). Woody debris is defined as containing at least 50% of woody material by volume.
- Properly designed coconut matting or other rolled erosion control products can be used where debris from land clearing is unavailable.

The woody debris layer from land clearing will provide substantial protection for typical flood flows. The debris layer will extend up to bankfull depth in the main channel, and along the entire length of the vegetated waterway. But there is a risk of failure, depending on the extremity of the floods and quality control during placement of the debris mixed with topsoil. Sacrificial zones of gravel armouring will be provided at regular intervals to provide a second line of defence in the event of failure. The sacrificial zone of armour material is a contingency (second line of defence) and the material volume is a small fraction of the armour that would be required for a purely structural design. The sacrificial armouring will be mobilized during high flow events and will be transported downstream to "heal" short stretches that have experienced some erosion. Deposits of sacrificial armouring with a D_{50} of 100 mm are proposed to be placed to a depth of 1.5 m and over a length of 1.5 m at intervals of 30 m. The armouring will be placed up to bankfull depth in the main channel. Together, the debris and sacrificial armouring will provide time for vegetation to become re-established, after which no armouring will be required.

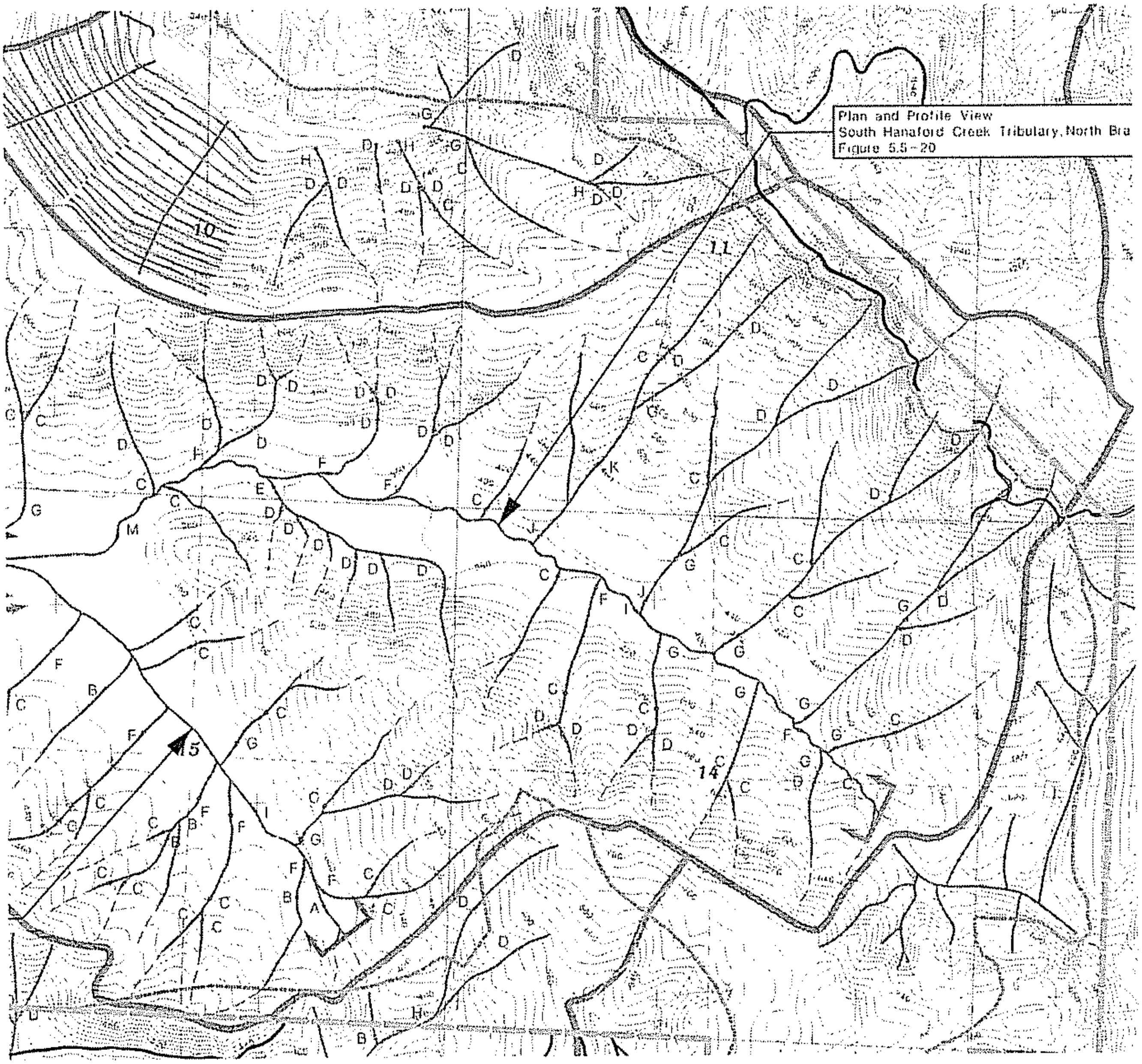

Figure 1 Example of a Drainage System Designed using the Geomorphic Approach

Alluvial Channels

The design of the alluvial channels is also based on replication of natural analogues. The alluvial channels will be required for drainage areas that exceed 2 ha. Field observations show that alluvial channels have bed materials with a D_{50} of less than 64 mm, indicating that armouring with material of a significantly larger D_{50} is not necessary in the long-term. Hence, a D_{50} of between 75 and 100 mm was considered since some bed load transport is acceptable (as in natural systems) in the geomorphic approach. The typical alluvial channel was proposed to be armoured with either gravel or pit run with a recommended D_{50} of 75 mm and to a depth of 0.3 m or a D_{50} of 100 mm to a depth of 0.5 m, depending on drainage area. These depths of armour layer exceed the usual criteria of 2 to 3 times D_{50}, thus providing extra sources of bed material to accommodate bed material transport. The armouring will be placed up to bankfull depth and free-board, and along the entire length of the alluvial channels. Larger armour (D_{50} of 200 mm) is provided in trenches of dimensions 1.2 m x 1.2 m at intervals of about 30 m to provide for self-healing capability in the event of extreme floods.

Sedimentation Ponds

Short-term surface water effects may include changes in runoff and increased soil loss. Within the first year of seeding or re-vegetation, soil erosion and surface runoff from the reclaimed watersheds will potentially be higher than the pre-mining conditions. Therefore, downstream sediment ponds are necessary through the transition period. Existing sedimentation ponds, designed to handle flows from mined areas, can generally fulfil this function.

Compliance of Geomorphic Design with Regulations

Reclamation drainage regulations generally require that drainage channels be able to safely convey flows from pre-specified design storms, such as, the 25-year 24-hr design storm. Under a purely structural design, any armouring material necessary to satisfy the design criteria should not move during the design flood event since displacement could uncover the erodible underlying materials. In a geomorphic approach, movement of some armouring material is acceptable because of the second line of defence, so that limited displacement does not result in catastrophic failure. This process occurs in nature and is the means by which channels adjust themselves to convey runoff through variable environmental conditions. Natural channels can sustain flows from far more extreme events than from, for example, the 25-year 24-hr storm without long-term negative impacts. Hence, the geomorphic approach allows for armour material sizes that are smaller than the D_{50} of a design by the structural approach. Designs based on the geomorphic approach comply with the philosophy of drainage regulations because the erodible underlying materials are properly protected. The protection is provided, not by an immobile cover layer, but, by a mobile and continually replenishing cover layer, just as in natural systems.

Summary

In a geomorphic approach, the designer attempts to emulate the dynamic variability and self-healing capability of natural drainage systems. Channels are allowed to mature by gradual degradation and aggradation, with erosion rates comparable to the natural environment. By empirical emulation of natural channels, a geomorphic approach provides a means of achieving sustainable and effective surface runoff drainage. The key advantages of a geomorphic design over a purely structural approach are:

- Geomorphologically sustainable landscapes and channel slopes
- Reduced size of armouring material
- Minimum reliance on due diligence of site owner for future maintenance
- "Walk-away" or maintenance-free design and reduced liability in the long-term

Additional benefits include aquatic productivity, vegetation diversity, wildlife escape habitat with an undulating topography, and improved aesthetics.

References

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