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COST-EFFECTIVE AND RISK-INFORMED DYKE DESIGN FOR BARRAGE INFRASTRUCTURE PROJECTS: A PARAMETRIC SLOPE STABILITY AND PROJECT MANAGEMENT ANALYSIS

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ABSTRACT

Large barrage and flood-control projects require dyke designs that are safe, practical to construct, and affordable under changing hydraulic and geotechnical conditions. Failure of a dyke can cause flooding, infrastructure damage, disruption of agricultural activities, and major economic losses. Although dyke stability is mainly a geotechnical issue, it is also important for construction project management because soil properties and dyke geometry affect construction quantities, cost, risk, and long-term performance. This study evaluates the stability of the proposed Sindh Barrage Project in Pakistan using a parametric slope-stability approach. The effects of soil unit weight, cohesion, and internal friction angle on the factor of safety (FOS) were examined using five limit-equilibrium methods: Ordinary, Janbu, Bishop, Spencer, and Morgenstern–Price. The results show that increasing soil unit weight reduces the FOS, while higher soil cohesion significantly improves slope stability. An increase in the internal friction angle also improves stability. The findings demonstrate the importance of linking geotechnical safety with construction planning, material quality, cost, and risk management. For the investigated 2:1 slope configuration, careful control of critical soil properties is important for maintaining adequate stability. The study provides a practical decision-support approach for project managers involved in the design and construction of large-scale barrage and flood-control infrastructure.

Keywords: *dyke design, barrage project, project management, slope stability, geotechnical risk, limit equilibrium; infrastructure resilience.*

1. Introduction

River flood control and water-management infrastructure are critical for the economic and social development of river flood-prone and water-scarce regions. Indus River system is of special significance for agriculture, irrigation, drinking water supply, ecosystems and a significant chunk of national economic activity in Pakistan. Thus, the planning and implementation of barrage infrastructure must consider the hydraulic and structural aspects as well as the effective management of geotechnical, environmental, financial and construction risks.

A dykes is an earthwork used to regulate and store water, and to prevent flooding on low-lying land. They are affected by seepage, geometry, soil properties, groundwater conditions, water level changes, construction quality and hydraulic loading. The consequences of failure may be far reaching, not just on the physical structure, including floods, loss of agricultural land, damage to infrastructure, displacement, and disruption to economic activities.

These challenges are put in the perspective of

the proposed Sindh Barrage Project. The project includes barrage structures and reservoir dykes, drainage channels and downstream protection works. The dyke system is therefore an important component of the project that could impact the overall performance and risk profile of the infrastructure project.

Engineering parameters (cohesion, friction angle, unit weight, factor of safety) are the traditional slope-stability parameters. But from the project-management point of view, there are also, to say the least, practical implications to these parameters. For instance, better soil may lead to better stability but also could involve more material processing, transportation, testing, and compaction. The same applies if slope of the dyke increases, as construction quantities may diminish, but with a probable decrease of factor of safety.

Therefore, a compromise between safety, cost, construction needs and project risk is required when designing dykes. This study thus recasts the problem of dyke stability as a project-management decision problem in the construction industry.

Research Questions

RQ1: How do soil unit weight, cohesion, and friction angle influence the stability of the proposed Sindh Barrage dyke?

RQ2: Which geotechnical parameters have the greatest influence on the factor of safety?

RQ3: How can slope-stability results support cost-effective and risk-informed construction project management?

RQ4: What project-management considerations should be incorporated into dyke design and construction planning?

2. Literature Review

2.1 Dyke Stability and Infrastructure Risk

Changes in water levels and seepage conditions are typical conditions on earth dykes. They may thus be quite different when they are built, when they are in steady seepage and when they undergo a very rapid drawdown. Rapid drawdown is of special concern because the external water level may fall at a faster rate than the pore-water pressure can dissipate within the embankment, which can decrease the effective stress and slope stability.

Limit-equilibrium approaches are useful for the estimation of the relationship between the resisting and driving forces and are widely used in slope-stability analysis. The assumptions about interslice forces and equilibrium are different in different methods. Some common methods for slope analysis are the Ordinary, Janbu, Bishop, Spencer and Morgenstern–Price methods.

But, for larger projects, technical stability is not independent of project risk. Increased quantities of construction materials may be necessary to attain a high factor of safety with a design, but lead to greater project costs and construction time. On the other hand, a low cost set-up with poor stability could mean that the project would have a high failure risk.

2.2 Geotechnical Parameters and Factor of Safety

Three principal soil parameters are examined in this study:

unit weight (γ);

cohesion (c); and

internal friction angle (φ).

he unit weight has an influence on the gravitational forces acting on the slope. Driving forces may be increased as the unit weight increases, which may lead to a decrease in the factor of safety.

Cohesion is a factor in shear strength and will tend to increase slope stability overall. But cohesion can be influenced by moisture conditions, compaction, soil structure and stress history.

The internal friction angle is the coefficient of frictional shear strength of the soil. The higher the angle of friction, the more resistant the object will be to sliding. These parameters are also significant for project management in terms of construction quality and material-control parameters. To ensure a given soil strength, therefore, it is necessary to use the right material, manage moisture, compact the soil properly, and utilize laboratory testing and field quality assurance.

3. Methodology

3.1 Research Design

Parametric case-study design was used with a quantitative approach. The proposed Sindh Barrage Dyke was considered as infrastructure

case while alteration of soil properties was considered for studying their effects on slope stability.

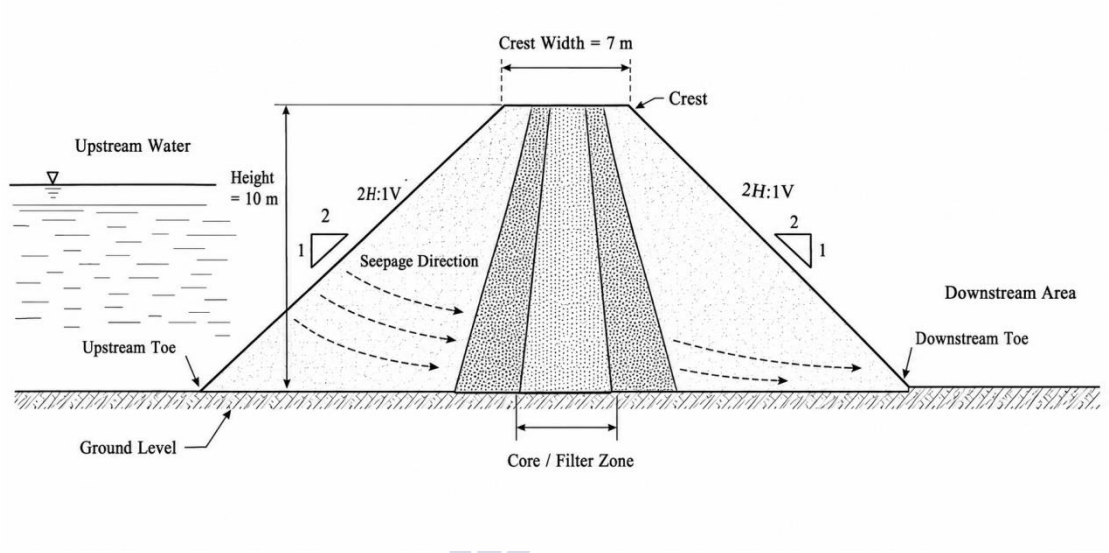
The analysis was carried out with GeoStudio 2012, including SLOPE/W and SEEP/W modules. Comparisons of stability outcomes were made using limit-equilibrium methods.

The following basic design assumptions were made:

dyke height: approximately 10 m;

- crest width: approximately 7 m;
- slope configuration: 2H:1V;
- seismic effects: excluded from the presented analysis;
- principal soil parameters: γ, c and φ.

Figure 1



3.2 Parametric Analysis

Three sensitivity analyses were conducted.

Model A: Unit Weight

Unit weight was varied between 11 and 21 kN/m³ while cohesion and friction angle were held constant.

Model B: Cohesion

Cohesion was varied from 100 to 180 kPa while other parameters remained constant.

Model C: Friction Angle

The internal friction angle was varied from 5° to 22° while unit weight and cohesion remained constant.

The factor of safety was calculated using five limit-equilibrium methods.

4. Results

4.1 Effect of Unit Weight

The results demonstrate a clear negative relationship between soil unit weight and factor of safety.

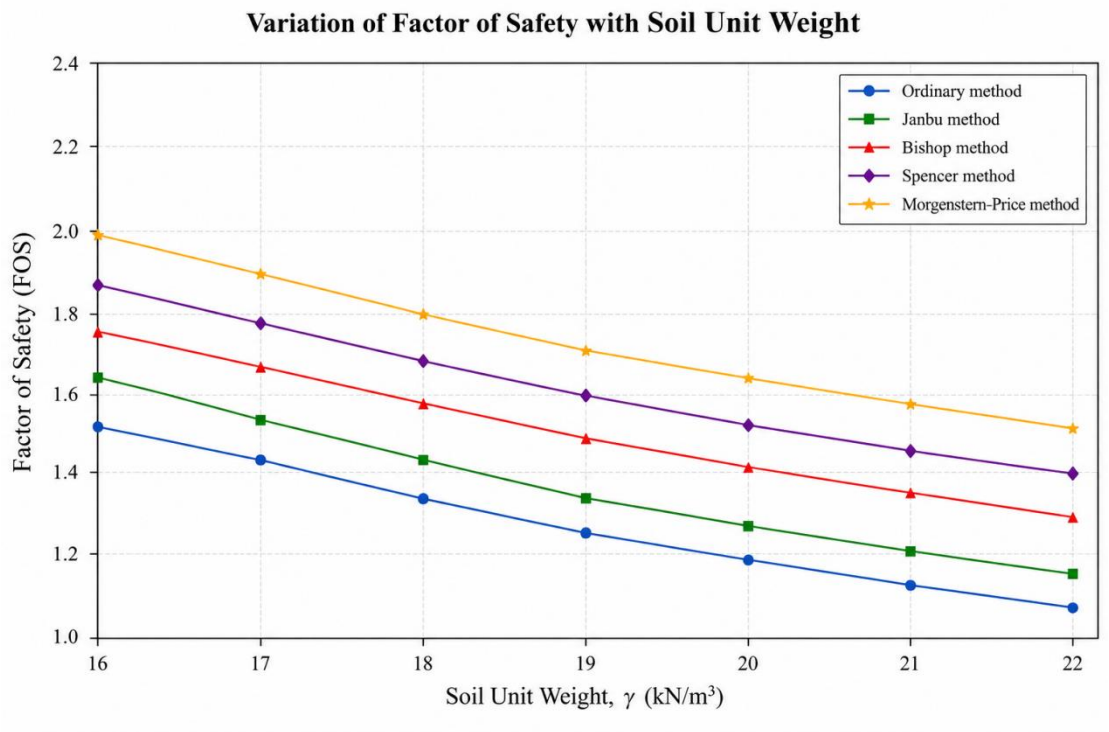
Table 1. Effect of unit weight on factor of safety

Unit weight (kN/m³)	Ordinary	Janbu	Bishop	Spencer	Morgenstern–Price
11	17.15	15.77	17.24	17.23	17.22
15	10.48	9.84	10.55	10.52	10.64
17	8.76	8.25	8.81	8.80	8.76
18	8.08	7.62	8.12	8.11	8.12
19	7.46	7.08	7.53	7.52	7.52
20	6.98	6.62	7.02	7.00	7.01
21	6.54	6.21	6.58	6.57	6.57

The results show a consistent decline in FOS across all methods as unit weight increases. Using the Bishop method, for example, FOS decreases from 17.24 at 11 kN/m³ to 6.58 at 21 kN/m³, representing a substantial reduction.

From a project-management perspective, this finding emphasizes the importance of material-density control and compaction management. Construction teams must achieve required density without unintentionally increasing the loading conditions beyond the assumptions used in design.

Figure 2



4.2 Effect of Cohesion

Cohesion demonstrated a positive relationship with factor of safety.

Table 2. Effect of cohesion on factor of safety

Cohesion (kPa)	Ordinary	Janbu	Bishop	Spencer	Morgenstern–Price
100	6.26	5.94	6.31	6.31	6.32
110	6.88	6.51	6.92	6.91	6.92
120	7.49	7.08	7.53	7.52	7.52
140	8.71	8.23	8.74	8.73	8.74
160	9.92	9.37	9.96	9.95	9.95
180	11.13	10.52	11.17	11.16	11.17

The Bishop FOS increases from 6.31 at 100 kPa to 11.17 at 180 kPa. This represents an increase of approximately 77%.

This finding has direct project-management implications. Improving soil cohesion can increase stability, but achieving higher-strength materials may require improved material selection, moisture control, stabilization, or greater compaction effort. These interventions can affect project cost and schedule.

4.3 Effect of Internal Friction Angle

The internal friction angle also produced a positive relationship with FOS.

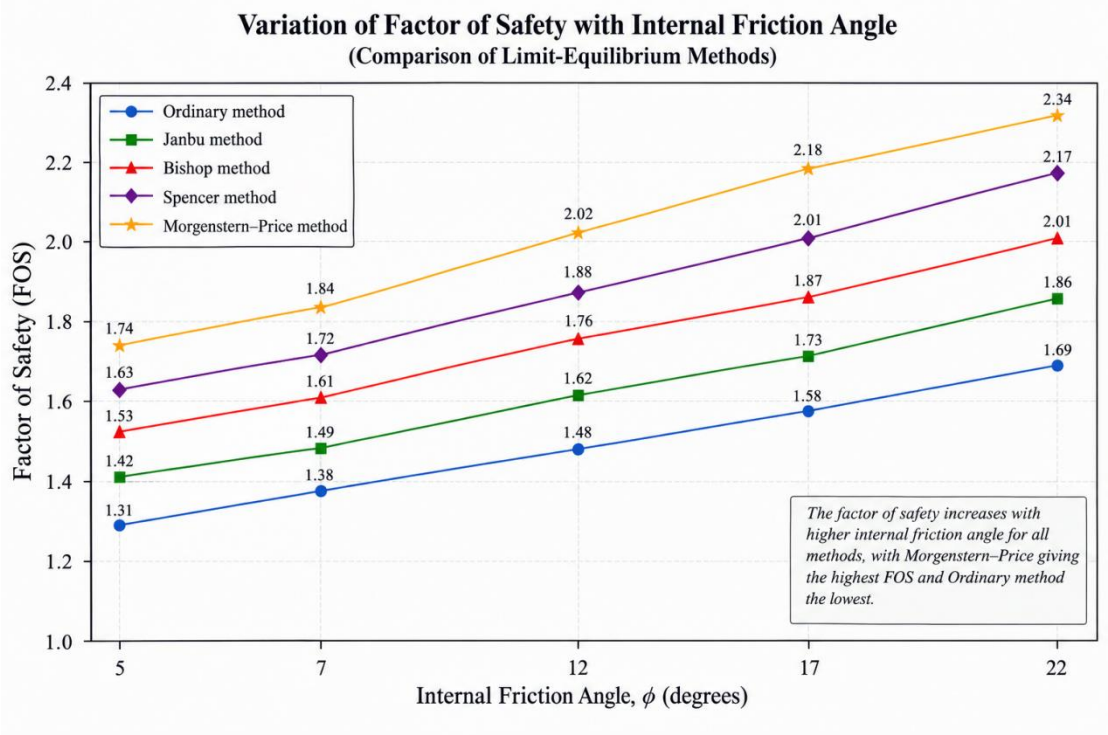
Table 3. Effect of friction angle on factor of safety

φ (degrees)	Ordinary	Janbu	Bishop	Spencer	Morgenstern–Price
5	7.49	7.08	7.53	7.52	7.52
7	7.58	7.18	7.63	7.62	7.62
12	7.87	7.40	7.89	7.87	7.87
17	8.02	7.63	8.14	8.13	8.13
22	8.25	7.88	8.41	8.40	8.40

The Bishop FOS increases from 7.53 at 5° to 8.41 at 22°. Compared with cohesion, the increase is more moderate.

This suggests that, within the investigated parameter range, cohesion represents a more influential variable than friction angle. This distinction is important when project managers prioritize quality-control resources.

Figure 3



5. Integrated Project Management Analysis

The technical results provide several important implications for construction project management.

5.1 Safety–Cost Trade-Off

Construction quantities are directly related to Dyke geometry. A flatter slope will normally require more fill material and take up more land than a steeper slope, which will in turn require less fill material but may offer less stability.

Project managers should not only consider minimum construction cost when they choose the geometry of their slopes. The following items should be taken into account when formulating a suitable decision framework: Safety + Cost + Constructability + Risk + Environmental Impact + Schedule

This transforms the decision about slope design from a technical to a project-management decision.

5.2 Construction Quality Management

The results demonstrate that soil parameters have a substantial influence on stability. Consequently, project quality management should include:

- material testing;
- moisture-content monitoring;

- compaction testing;
- density verification;
- shear-strength testing;
- field inspection; and
- documentation of construction layers.

Failure to achieve design soil parameters can produce a discrepancy between design FOS and actual field performance.

5.3 Risk Management

Dyke failure represents a high-consequence infrastructure risk. Therefore, project managers should establish a geotechnical risk register covering:

Risk	Potential consequence	Management response
Excessive unit weight	Reduced FOS	Density and compaction control
Low cohesion	Reduced shear resistance	Material testing and stabilization
Low friction angle	Lower stability	Appropriate material selection
Excessive seepage	Pore-pressure increase	Drainage/filter systems
Rapid drawdown	Potential slope instability	Hydraulic monitoring and staged operation
Poor construction quality	Difference between design and actual performance	QA/QC program
Inadequate monitoring	Late identification of failure mechanisms	Instrumentation and inspection

This approach allows geotechnical uncertainty to be incorporated into the project's overall risk-management system.

6. Proposed Project-Management Framework

The findings support a five-stage decision framework for dyke projects:

Stage 1 — Planning: Identify hydraulic, geotechnical, environmental and socioeconomic risks.

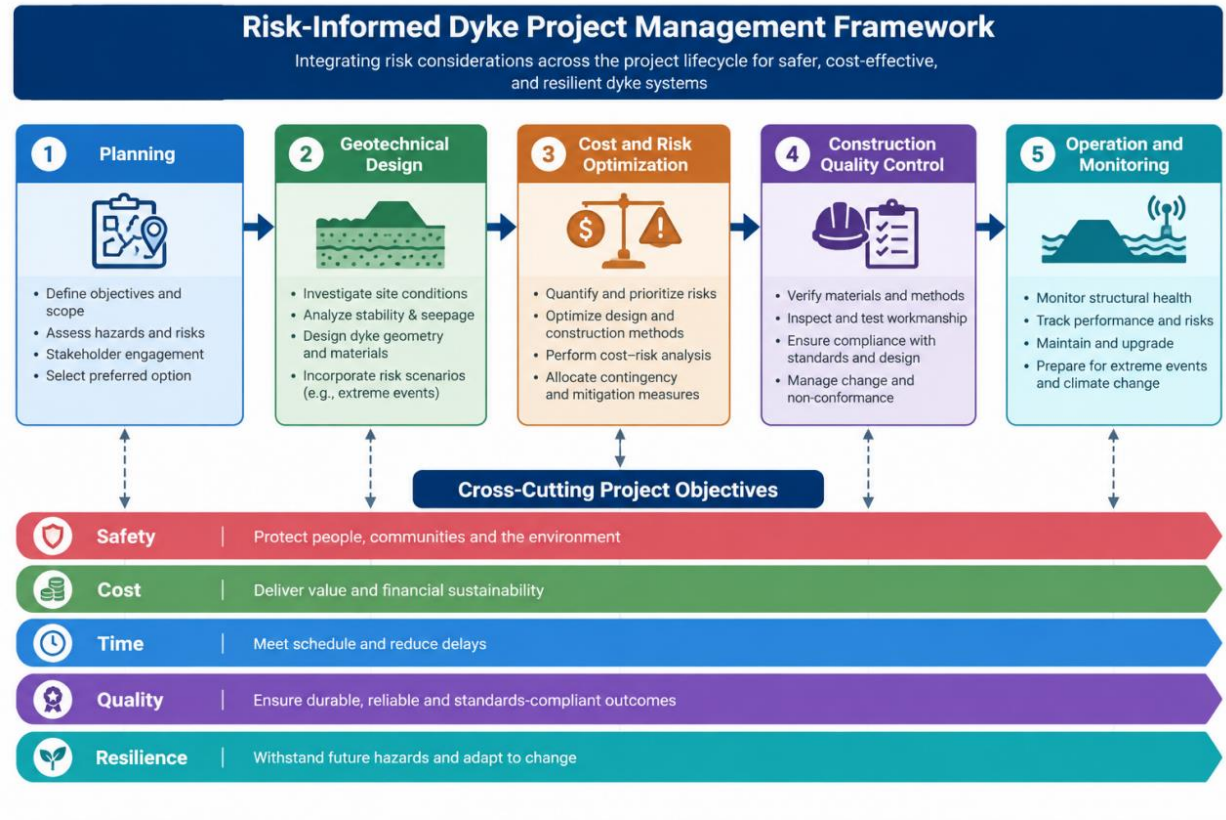
Stage 2 — Design: Evaluate alternative slopes, materials and drainage configurations.

Stage 3 — LCA/Cost Assessment: Compare construction quantities, costs, environmental effects and expected risk.

Stage 4 — Construction: Implement material testing, compaction control and quality assurance.

Stage 5 — Operation and Monitoring: Monitor water levels, seepage, deformation and slope performance.

Figure 4 placement — Prompt:



7. Discussion

The analysis shows that the stability of the dykes is strongly dependent on the soil properties. The unit weight has a negative correlation with FOS and positive correlation with cohesion and internal friction angle. Of the variables studied, cohesion causes a significant alteration of FOS.

The outcomes also show fairly consistent patterns among the five limit-equilibrium methods. Numbers are slightly different, but the direction of the relationships is the same. This adds to confidence in the overall parametric trend, but won't remove uncertainty of soil properties, groundwater conditions, model assumption and field variability. The most significant implication for construction project managers is that the design optimization should not be based on maximizing the FOS. Too conservative designs can be very difficult to construct and too aggressive designs can lead to undue risks. The best answer should therefore be a combination of engineering reliability, project economics and constructability.

In the context of Sindh Barrage Project, this is particularly true as the dyke system is part of a larger infrastructure network. An uncontrolled failure of a dyke not only would have an impact on the dyke system, but also on society downstream, irrigation schemes, transport and farming. Hence, the overall project's risk-management and resilience plan should include dyke stability.

8. Conclusion

In this study, the stability of an intended dyke of Barrage in Sindh from a geotechnical and project management point of view has been discussed. The results of the parametric analysis showed that the factor of safety is sensitive to the soil unit weight, cohesion and internal friction angle.

In all the limit-equilibrium methods analysed, an increase in unit weight led to a decrease in FOS. On the other hand, an increase in cohesion significantly increased stability, but an increase in the friction angle led to a relatively smaller but positive increase in stability. The results indicate that the dyke design should not be considered just as a geotechnical optimization problem. The right soil, compaction, drainage, slope geometry, and construction quality directly affect project cost, schedule, risk and long-term infrastructure resilience.

The study thus proposes that the slope stability analysis be combined with cost estimation, risk evaluation, quality management and construction plan in practice. A risk-based project-management process allows project teams to determine key soil parameters, define quality control requirements, evaluate design options and minimize the chance of catastrophic failure of infrastructure.

Further research is needed to continue analysis up to probabilistic slope stability analyses, rainfall and groundwater conditions, rapid drawdown simulations, flood scenarios generated by climate changes, detailed analyses with respect to quantity/cost optimization, and field geotechnical data. This would contribute to a more holistic framework in achieving the optimal performance of the dyke at Sindh Barrage in the context of sustainable and resilient infrastructure project management.

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