STABILITY OF LANDFILLS IN HILLY REGIONS

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STABILITY OF LANDFILLS IN HILLY REGIONS

by

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This Thesis is dedicated to the knowledge of

“LORD JAGANNATH” and “BANKE BIHARI JI”

&

My Father

Late. Shri Pabitra Mahanta

CERTIFICATE

This is to certify that the thesis entitled "**STABILITY OF LANDFILLS IN HILLY REGIONS**" being submitted by **Mr. Abinash Mahanta** to the **Indian Institute of Technology Delhi** for the award of degree of **DOCTOR OF PHILOSOPHY** is a record of bonafide research work carried out by him under our guidance and supervision in conformity with the rules and regulations of the Indian Institute of Technology Delhi. The thesis work, in our opinion, has reached the standard fulfilling the requirements for Doctor of Philosophy degree. The research report and results presented in this thesis have not been submitted, in part or full, to any other university or Institute for the award of any degree or diploma.

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ABSTRACT

Landfills are usually located on outskirts of the cities on flat ground in plain regions. In hilly regions, flat ground for landfilling is scarce. Available unconventional landforms such as sloping grounds, side-hills, valleys, gullies, draws, etc. have to be utilized for making a landfill conforming to regulatory requirements. From literature it is observed that, in hilly regions, landfills are generally constructed at the following potential locations: (a) on a sloping ground; (b) on the side of a hill; and (c) within a valley. However there are several documented major failure cases of landfills in hilly regions which were constructed at such locations.

On the comparatively flat ground in hilly regions potential mode of failure is rotational failure which occurs through the waste mass. Whereas on sloping terrains in hilly regions, the failure along the inclined liner system influences the stability of landfills. The shape of the landfills are different in different locations based on the different shape of the terrain/landforms. This fact differs the stability of landfills in hilly regions from plain regions (flat ground). Literature related to the stability of landfills in hilly regions are studied and the present study is undertaken as there is no specific guidelines for design of landfills in hilly regions could be found. The associated challenge is the lack of understanding of the parameters governing the stability of engineered landfills in hilly regions and their consequences in design. Literature related to stability enhancement of landfills with earthen toe berm are not specific about the extent of stability enhancement of landfills in case of hilly regions.

The objective of the present study was to assess the influence of critical parameters on stability of landfills in hilly regions at the three possible locations- sloping ground, side

of a hill, and in a valley. The influence of 10 variables on stability has been studied, normally, shear strength parameters of waste as well as of interfaces in composite liner system, parameters related to landfill geometry (base length, height of waste, landfill front slope) and terrain/landform geometry (base slope, back slope (side-hill), valley side slope, valley base width, and tapering angle). Each variable has been varied with a range arrived at on the basis of extensive literature study. The influence of each parameter on stability of sloping-ground, side-hill and valley landfills has been investigated by conducting slope stability analyses on a base case and then by varying the values of the parameters within their respective ranges.

Limit equilibrium methods have been adopted for slope stability analysis. For the sloping ground and side-hill landfill, only two dimensional (2D) limit equilibrium analyses have been performed whereas for the valley fill landfills, three dimensional (3D) limit equilibrium method (LEM) of analysis over and above 2D has been adopted. The analysis have been performed using commercially available 2D (Slope/W) and 3D (Slide3) limit equilibrium based software. In both 2D and 3D analysis results are obtained for Morgenstern & Prices's (M&P) method or General Limit Equilibrium (GLE) method.

The results and findings of the present study provide a better understanding of the critical parameters which governs the stability of landfills in hilly regions and extent of their influence. From the present study, some major findings for sloping-ground, side-hill and valley landfills have emerged. These findings are new and useful for stability analysis of landfills in hilly regions.

(a) In case of sloping-ground landfills, the most important factor is the critical base inclination ($\beta_{b\text{(critical)}}$) beyond which the failure of the landfill occurs along the entire weakest interface of the liner system. When $\beta_b < \beta_{b\text{(critical)}}$, the failure occurs through the waste mass (usually circular/planar) and along the weakest interface of the liner system (usually planar).

(b) In case of side-hill landfills, the most important factor is the influence of the back slope (side-hill) which in turn depends on the base length of the landfills. A critical base length $L_b*_{(critical)}$, governs the zone in which the influence of back slope is observed. $L_b*_{(critical)}$ is in the range of four to eight (4 to 8) times of height of the waste, H_w*. When $L_b* > L_b*_{(critical)}$, back slope has no influence on stability. However when $L_b* < L_b*_{(critical)}$, the influence of back slope is usually to lower the stability of the landfill as in such cases the failure of the landfill occurs along entire weakest interface of the composite base and back liner system.

(c) In case of valley landfills, the most important factor is the critical valley front base width, ($B_{VF(critical)}$) upto which the influence of resistance offered by the valley side slopes is observed. The resistance offered by the valley side slopes enhances the stability of a valley landfill. When $B_{VF} > B_{VF(critical)}$, the influence of side slopes is nominal. However when $B_{VF} < B_{VF(critical)}$, influence of side slopes causes FoS to rise.

(d) The three factors such as $\beta_{b(critical)}$ (in case of sloping-ground landfills), $L_{b*(critical)}$ (in case of side-hill landfills), and $B_{VF(critical)}$ (in case of valley landfills) are influenced by the relative shear strength of the waste and interface shearing resistance of the weakest interface of the composite liner system. High shear strength of the waste and low interface shear strength (along the weakest interface of the base liner system) causes a $\beta_{b(critical)}$ to be low and vice-versa (in case of sloping-ground landfills); causes $L_b*_{(critical)}$ to be high and vice-versa (in case of side-hill landfills); and causes $B_{VF(critical)}$ to be high and vice-versa (in case of valley landfills).

सार

लैंडफिल आमतौर पर मैदानी क्षेत्रों में समतल भूमि पर शहरों के बाहरी इलाके में स्थित होते हैं। पहाड़ी क्षेत्रों में, लैंडफिलिंग के लिए समतल जमीन दुर्लभ है। उपलब्ध अपरंपरागत लैंडफॉर्म जैसे ढलान वाले मैदान, साइडहिल्स, घाटियों, गलियों, ड्रॉ आदि का उपयोग लैंडफिल को विनियामक आवश्यकताओं के अनुरूप बनाने के लिए किया जाना है। साहित्य से यह देखा गया है कि, पहाड़ी क्षेत्रों में, लैंडफिल का निर्माण आम तौर पर निम्नलिखित संभावित स्थानों पर किया जाता है- (a) ढलान वाली जमीन पर; (b) किसी पहाड़ी के किनारे; और (c) एक घाटी के भीतर। हालांकि पहाड़ी क्षेत्रों में लैंडफिल के कई असफल दस्तावेज हैं जो ऐसे स्थानों पर बनाए गए थे।

पहाड़ी क्षेत्रों में तुलनात्मक रूप से समतल जमीन पर विफलता की संभावित विधा घूर्णी विफलता है जो अपशिष्ट द्रव्यमान के माध्यम से होती है। जबकि पहाड़ी क्षेत्रों में ढलान वाले इलाकों में, झुका हुआ लाइनर प्रणाली के साथ विफलता लैंडफिल की स्थिरता को प्रभावित करती है। भूभाग भूआकृतियों के विभिन्न आकार के आधार पर विभिन्न स्थानों में लैंडफिल का आकार भिन्न होता है। यह तथ्य मैदानी क्षेत्रों समतल जमीन से पहाड़ी क्षेत्रों में लैंडफिल की स्थिरता को अलग करता है। पहाड़ी क्षेत्रों में लैंडफिल की स्थिरता से संबंधित साहित्य का अध्ययन किया जाता है और वर्तमान अध्ययन किया जाता है क्योंकि पहाड़ी क्षेत्रों में लैंडफिल के डिजाइन के लिए कोई विशेष दिशानिर्देश नहीं है। संबंधित चुनौती पहाड़ी क्षेत्रों में इंजीनियर लैंडफिल की स्थिरता और उनके डिजाइन में परिणाम को नियंत्रित करने वाले मापदंडों की समझ की कमी है। मिट्टी के बरम के साथ लैंडफिल की स्थिरता बढ़ाने से संबंधित साहित्य पहाड़ी क्षेत्रों के मामले में लैंडफिल की स्थिरता बढ़ाने की सीमा के बारे में विशिष्ट नहीं हैं।

वर्तमान अध्ययन का उद्देश्य पहाड़ी क्षेत्रों में तीन संभावित स्थानों- ढलान वाली जमीन, एक पहाड़ी के किनारे, और एक घाटी में स्थिरता के लिए महत्वपूर्ण मापदंडों के प्रभाव का आकलन करना था। स्थिरता पर 10 चर के प्रभाव का अध्ययन किया गया है, सामान्य रूप से, अपशिष्ट शक्ति के कतरनी शक्ति मापदंडों के साथ-साथ समग्र लाइनर सिस्टम में इंटरफेस, लैंडफिल ज्यामिति से संबंधित पैरामीटर (आधार लंबाई, अपशिष्ट की ऊंचाई, लैंडफिल फ्रंट ढलान) और इलाके / लैंडफॉर्म ज्यामिति (बेस ढलान, बैक स्लोप (साइड-हिल), वैली साइड स्लोप, वैली बेस चौड़ाई और टेपरिंग एंगल)। प्रत्येक चर व्यापक साहित्य अध्ययन के आधार पर एक सीमा के साथ विविध किया गया है। ढलान-जमीन, साइड-हिल और वैली लैंडफिल की स्थिरता पर प्रत्येक पैरामीटर के प्रभाव की जांच एक आधार मामले पर ढलान स्थिरता विश्लेषण आयोजित करके और फिर उनकी संबंधित सीमाओं के भीतर मापदंडों के मूल्यों को अलग-अलग करके की गई है। ढलान स्थिरता

विश्लेषण के लिए सीमा संतुलन के तरीकों को अपनाया गया है। ढलान वाली जमीन और साइड-हिल लैंडफिल के लिए, केवल दो आयामी (2 डी) सीमा संतुलन विश्लेषण किया गया है, जबकि घाटी भरने के लिए लैंडफिल, तीन आयामी (3 डी) सीमा संतुलन विश्लेषण (एलईएम) विश्लेषण के गठन और 2 डी से ऊपर अपनाया गया है। विश्लेषण व्यावसायिक रूप से उपलब्ध 2D (स्लोप / डब्ल्यू) और 3 डी (स्लाइड 3) सीमा संतुलन आधारित सॉफ्टवेयर का उपयोग करके किया गया है। 2 डी और 3 डी दोनों विश्लेषण में Morgenstern & Price (M & P) विधि या सामान्य सीमा संतुलन (GLE) विधि के लिए परिणाम प्राप्त किए जाते हैं। वर्तमान अध्ययन के परिणाम और निष्कर्ष उन महत्वपूर्ण मापदंडों की बेहतर समझ प्रदान करते हैं जो पहाड़ी क्षेत्रों में लैंडफिल की स्थिरता और उनके प्रभाव की सीमा को नियंत्रित करते हैं। वर्तमान अध्ययन से, ढलान-जमीन, साइड-हिल और घाटी लैंडफिल के लिए कुछ प्रमुख निष्कर्ष सामने आए हैं। ये निष्कर्ष पहाड़ी क्षेत्रों में लैंडफिल के स्थिरता विश्लेषण के लिए नए और उपयोगी हैं।

(a) ढलान जमीन लैंडफिल के मामले में, सबसे महत्वपूर्ण कारक महत्वपूर्ण आधार झुकाव ($\beta_{b(\text{critical})}$) है जिसके आगे लैंडफिल की विफलता लाइनर सिस्टम के पूरे सबसे कमजोर इंटरफेस के साथ होती है। जब $\beta_b < \beta_{b(\text{critical})}$, विफलता अपशिष्ट द्रव्यमान आमतौर पर परिपत्र प्लेनर और लाइनर सिस्टम आमतौर पर प्लानर के सबसे कमजोर इंटरफेस के साथ होती है।

(b) साइड‌ हिल लैंडफिल के मामले में, सबसे महत्वपूर्ण कारक बैक स्लोप | साइड‌हिल का प्रभाव है जो बदले में लैंडफिल की आधार लंबाई पर निर्भर करता है। एक महत्वपूर्ण आधार लंबाई $L_b{}^*{}_{(\text{critical})}$, उस क्षेत्र को नियंत्रित करता है जिसमें बैक स्लोप का प्रभाव देखा जाता है। $L_b{}^*{}_{(\text{critical})}$, चार से आठ से बार कचरे की ऊंचाई, $H_w{}^*$ की सीमा में है। जब $L_b{}^* > L_b{}^*{}_{(critical)}$, बैक स्लोप का स्थिरता पर कोई प्रभाव नहीं पड़ता है। हालांकि जब $L_b{}^* < L_b{}^*{}_{(critical)}$, बैक स्लोप का प्रभाव आमतौर पर लैंडफिल की स्थिरता को कम करने का होता है क्योंकि ऐसे मामलों में लैंडफिल की विफलता समग्र बेस और बैक लाइनर सिस्टम के पूरे सबसे कमजोर इंटरफेस के साथ होती है।

(c) घाटी लैंडफिल के मामले में, सबसे महत्वपूर्ण कारक महत्वपूर्ण वैली फ्रंट बेस चौड़ाई, ($B_{VF(\text{critical})}$) है, जिसमें वैली साइड स्लोप द्वारा प्रस्तुत प्रतिरोध का प्रभाव देखा जाता है। घाटी की ओर ढलान द्वारा प्रस्तुत प्रतिरोध एक घाटी लैंडफिल की स्थिरता को बढ़ाता है। जब $B_{VF} > B_{VF(\text{critical})}$, साइड स्लोप का प्रभाव नाममात्र है। हालाँकि जब $B_{VF} < B_{VF(critical)}$, साइड स्लोप्स के प्रभाव से FoS का उदय होता है।

(d) तीन कारक जैसे $\beta_{b(\text{critical})}$ (ढलान वाली जमीन लैंडफिल के मामले में), $B_{VF(\text{critical})}$ साइड‌हिल लैंडफिल के मामले में, और वैलिड लैंडफिल के मामले में समग्र लाइनर प्रणाली के सबसे

कमजोर इंटरफेस के अपशिष्ट और इंटरफ़ेस कतरनी प्रतिरोध के सापेक्ष कतरनी ताकत से प्रभावित है। कचरे की उच्च कतरनी शक्ति और कम इंटरफ़ेस कतरनी ताकत बेस लाइनर सिस्टम के सबसे कमजोर इंटरफेस के साथ एक $\beta_{b(\mathrm{critical})}$ का कारण बनता है कम और इसके विपरीत ढलान जमीन लैंडफिल के मामले में; $L_b{}^*{}_{(\mathrm{critical})}$ को उच्च और इसके विपरीत साइडहिल लैंडफिल के मामले में होने का कारण बनता है; और $B_{VF(\mathrm{critical})}$ का कारण बनता है और इसके विपरीत घाटी लैंडफिल के मामले में।

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LIST OF SYMBOLS AND NOTATIONS

CPHEEO	Central Public Health and Environmental Engineering Organisation
CPCB	Central Pollution Control Board
USA	United States of America
TPD	Tonnes per day
2D	Two dimensional
3D	Three dimensional
LEM	Limit equilibrium method
GM	Geomembrane
CCL	Compacted clay liner
cpd	Per capita per day
MSW	Municipal Solid Waste
FoS	Factor of safety
$FoS_{(critical)}$	Critical Factor of safety
FS	Failure Surface
$FS_{critical}$	Critical Failure Surface
H: V	Horizontal: Vertical, indicating inclination of slopes
$c^{/}$	Cohesion intercept
$\varphi^{/}$	Angle of shearing resistance

DST	Direct Shear Test
PDF	Probability density function
μ_δ	Mean
σ_δ	Standard Deviation
COV	Coefficient of variation
α_h	Horizontal seismic coefficient
α_v	Vertical seismic coefficient
W	Weight of slice mass
PHA	Peak horizontal accelearation
DM	Deformation Method
FE	Finite Element
FD	Finite Difference
GLE	General Limit Equilibrium
HDPE	High-Density Polyethylene
β_b	Base inclination
$\beta_{b(critical)}$	Critical base slope inclination
L_b*	Base length
$L_b*_{(critical)}$	Critical base length
B_b	Base width
H_w*	Height of waste
FCS	Final Cover Slope

β_s	Inclination of the back slope
B_{VF}	Valley Front Base Width
$B_{VF\ (critical)}$	Critical Valley Front Base Width
B_{VB}	Valley Back Base Width
B_T	Valley Top Width
Ψ	Valley Side Slope
θ	Tapering angle
c_α	Adhesion intercept
δ	Interface shearing angle
$\delta_{GM\text{-}CCL}$	Interface shearing angle of GM-CCL interface
h_w	Temporary leachate head
r_u	Pore water pressure ratio
FS_{CW}	Circular failure through the waste mass
$FS_{CW\text{-}PL}$	Circular failure through the waste mass and planar sliding along GM-CCL interface
$FS_{PW\text{-}PL}$	Planar failure through waste mass and planar sliding along GM-CCL interface
FS_{PL}	Planar sliding along entire GM-CCL interface of base liner system
Pl	Plane indicating section of a diagram
NF_{waste}	Normalizing factor for variability of shear strength of waste mass (for Chart- A and Chart-B)
$NF_{interface}$	Normalizing factor for variability of shear strength of GM-CCL interface

$FS_{PW\text{-}PL\ (over\text{-}berm)}$	Planar failure through the waste mass and sliding along the GM-CCL interface extends over the back slope of the earthen berm
$FS_{PL(over\text{-}berm)}$	Planar sliding along the whole GM-CCL interface extends over the back slope of the earthen berm
$FS_{PW\text{-}PL(under\text{-}berm)}$	Planar failure through the waste mass and sliding along the GM-CCL interface extends under the earthen berm
$FS_{PL(under\text{-}berm)}$	Planar sliding along the whole GM-CCL interface extends under the earthen berm
$H_w{*}_{critical}$	Height of waste corresponding to $FoS_{critical}$