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A Geographically Weighted Regression Kriging Approach for Mapping Swelling Potential of Garinono Formation Soil

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Abstract: The Beluran-Telupid road is notoriously known for its deterioration which sits on Garinono Formation soil and is rich with argillaceous melange. This contributed to inconvenience to motorists apart from being perilous when the subgrade of the road starts to degrade. A geographically weighted regression kriging was conducted along the road based on 25 samples to generate a swelling potential map. The results from the samples have reaffirmed the argillaceous nature of the soil due to the high composition of fine grains mainly clay, especially at the midsection. Nevertheless, after computation, most of the soils have medium swelling potential. After geographically weighted regression kriging was conducted, certain areas are defined as areas which have high swelling potential. Methodologies in this study increase the chances to validate swelling potentials and reduce the gap which is missing in the construction industry involving public road and geotechnical projects.

Keywords: Expansive soil, argillaceous, melange, swelling potential, kriging

1. Introduction

It is known to almost everyone especially Sabahans that the road linking Telupid to Sandakan, especially the stretch along Beluran is severely deteriorated and often labelled as the "moon surface road". The appalling experience stretches between Mile 28 and Mile 32 where the road is plagued with more than 20 major potholes and some are as deep as two feet (Chong, 2022). Many motorists complained that theroad is not only unsafe but treacherous as well which makes driving precarious. The outcome was attributed to frequent flooding. Countrymen began to feel frustrated and often unleashed their dissatisfied uproars on social media and called out all agencies involved and labelled politicians as perfidious. After years of lambasting the authorities and agencies, the Deputy Chief Minister and Works Minister of Sabah, Datuk Seri Bung Moktar Radin finally conceded and request the people to be patient as the newer Pan Borneo highway will resolve this issue. When this issue stirred the whole state into pandemonium and being

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politicised, the Deputy Works Minister of Malaysia, Datuk Arthur Kurup responded with multiple solutions based on quantum and period which starts with RM5 million to carry out immediate repair work and is due to be completed in two months (Vanar, 2022).

The flooding or water stagnation issues within that particular stretch of the road are the rationale behind the degradation of the road. Expansive clay and the increase of moisture content within the subgrade triggered uplift thrust which makes the road to be undulating before further deteriorating to other types or modes of road defect. This will not be solved if only the wearing course is repaired and/or patched without considering ground treatment works for the subgrade. Will the contingencies provided in the Pan Borneo Contract be sufficient to mitigate this issue during routine maintenance and periodical maintenance? Have the expansive clay issues been addressed and considered in the road corridor selection as well as the design of the road? Will this be a ubiquitous and omnipresent issue for infrastructure developments in the state of Sabah? It has to be resolved not only within that particular district but other districts which are afflicted by similar soil types due to the innate and inherited behaviour of argillaceous melange soil which is highly expansive. Nevertheless, this particular phenomenon must be first understood before mitigation through engineering works can be done instead of a recurrence of misspending on rectification works. Therefore, it is appropriate to identify the spatial distribution of expansive clay, mainly for argillaceous melange.

2. Literature Review

2.1 Regional Geology and Garinono Soil Properties

Garinono Formation is formed from Neogene's clastic sediment which consists dominantly of slump breccia with constituents made of sequences of interbedded mudstone, tuff, tuffite and minor sandstone and calcerite. The slump breccia which is a rock type composed of angular broken fragments of minerals or rocks cemented together by the fine-grained matrix - is made up of fragments and blocks of assorted rock types in a mudstone matrix, primarily of sandstone, limestone, chert, basalt, serpentinite and gabbro (Rodeano *et al.*, 2017).

Garinono Formation soil has both argillaceous and mélange properties due to its high content of clay or fine-grained content in its matrix. The high content of clay in Garinono soil was defined based on a finding made by Musta *et al*. (2019) where all soil samples contained clay and the presence of kaolinite and illite which exist in common expansive soils aside from the highly expansive montmorillonites (Chen, 1975). The average Liquid Limits and the average Plastic Indexes suggested that samples vary from low-plasticity to high-plasticity soils (Musta *et al.*, 2019). The other engineering properties indicate that this type of soil's strength through unconfined compression strength tests varies from very soft soil to very strong soil. Nevertheless, the soil is considered as low permeability and the addition of Moisture Content by 2.5% to 5.0% is substantial to degrade the overall strength. This leads to a high potential for slope failure (Musta *et al.*, 2018).

In the Soil Map of Sabah NB50-11 (Sandakan), the road sits on a few types of soil association which are predominantly Kretam moderate hills and Rumidi low hills and valley floor where the parental units are a combination of various types of rock – mainly Acrisols and Luvisols. The rest are on Kinabatangan floodplain, Lungmanis valley floors and Dalit moderate hills. The connotation from both Acrisols and Luvisols in soil taxonomy defines the clay behaviour of the soil which is notably weathered clay and slow activity clay for the former and high clay activity for the latter (ISRIC, n.d a; ISRIC, n.d. b). This leads to the different potential for swelling since both types coincide in a similar parental unit, the region as well as topography.

2.2 Standard Specifications on Argillaceous Materials and Road Hazards

The Standard Specification of Road Works by JKR explicitly mentioned argillaceous material unsuitability however, it was rarely discussed or observed in the Inspection and Test Plan. The onus on this issue in most road construction presents when such condition is not categorized as unsuitable material but a caveat in the sub-clause for suitable material. This leads many superintending officers, contractors and engineers to forsake any need to further validate and justify such material as unsuitable material as long as the soil properties are not combustible, sufficient plastic and liquid limit, not much loss of weight on ignition, and no substantial volumetric change.

The term argillaceous is silty in the French language whereby it is lithification that results in the progressive change from soft mud to stiff clay or greater strength, in which the mineral grains possesses a preferred orientation. It has a finer grain size in comparison to rudaceous and arenaceous which are comprised mainly of gravel and sands respectively for the clastic sedimentary rock group. Argillaceous rocks and/or material (hereafter known as argillaceous material) is a matrix which constitutes of rocks such as argillite, claystone, siltstone, mudstone, shale, clay shale, or marl and mainly of silt and/or appreciable clay particles or minerals. (Corominas *et al.*, 2014; O'Brien and Slatt, 1990). The semantics or nomenclature for the term 'rock' applies to residual soils as the soil is a by-product of disintegrated rock of Grade VI which has lost its original rock texture (Civil Engineering and Development Department, 2017).

Mélange is a heterogeneous mixture of rock materials in which derived from the mappable body of deformed rocks which are pervasively sheared, fine-grained, pelitic matrix, thoroughly mixed with angular or poorly sorted constituents such as tectonic fragments, blocks, or slabs of diverse origins and geological eras (McGraw-Hill, 2003). The presence of clay and related minerals such as kaolinite, illite, smectite and/or montmorillonites increased the risk of the soil being expandable.

Expansive soil is one of the main causes leading to pavement degradation based on internal factors. Conventionally, external factors such as traffic loadings were considered during the design stage and the risks of such dilapidation are averted. Nevertheless, internal factors are associated with pavement materials and subgrades. Swelling and shrinkage of subgrade materials are critical factors which affect the roughness and degradation of pavement. Expansive and/or swelling soils are associated with recurrent volume changes depending on the fluctuation of moisture content which leads to heaving or lifting apart from the loss of mass or collapse. This exacerbates the impact on light structures like roads and other infrastructures which cannot counteract such phenomenon (Fattah and Al-Adili, 2017).

Delamination of roads is a peril to motorists when it starts with cracks forming on the surface texture of the road due to swelling and hence, leads to hazards and potential mortality. Rusli *et al*. (2015) in their study on road accidents in Sabah render important findings when associating road geometry as the main reason for 19% (4,874) crashes along mountainous roads involving mainly passenger cars in self-accidents. Out of these crashes, 2317 or 47.5% are related to out-of-control issues and 60% of the drivers engaged in risky driving activities such as speeding and overtaking. A comparison was made between driving in good weather and adverse or during precipitation where it was found to have no significance in road accidents. Nevertheless, the odds of accidents increased when driving at night on mountainous roads due to visibility during manoeuvring as part of risky driving activities. With poor lighting and visibility as well as exposure to defective and delaminated pavement surfaces, there are tendencies for self-accidents. Although it was not mentioned in Rusli *et al*. (2015) that pavement surface is the nexus linking accidents and risky driving, it is significant that surface pavement plays an important role in triggering accidents, especially for heavy vehicles like trucks which occur substantially along the mountainous roads of Sabah. Chen, Chen and Wu (2011), reckoned that 80% of truck-related accidents are significantly influenced by road surface conditions and associated with traffic safety. Aside from pavement, slopes at both sides of the road and right-of-ways as well as daylight of the embankments are exposed to potential erosion. Exposed surfaces that experience swelling and breakdown will facilitate erosion (Fattah and Al-Adili, 2017). The dangers posed by expansive soil not only will affect the infrastructure and socioeconomic investment made but also endangers motorists. For that reason, argillaceous soils are not favoured as engineered fill or embankment materials.

2.3 Swelling Potential

Water is essential when discussing the swelling of soils, especially those which contain clay minerals. When soil is in contact with water, these clay minerals will absorb water which leads to a volume increase and stress depending on the boundary conditions as well as altering the mechanical behaviour such as reduction of strength and stiffness (Vergara and Triantafyllidis, 2016). This is apparent when it comes to expansive soil which is a problematic plastic unsaturated clay which resulted in swelling and shrinking when there is a change in moisture content which is often affected by cyclic wetting and wetting, mainly from precipitation and evapotranspiration. The outcome of this cycle leads to the initiation, propagation and enlargement of cracks as part of weathering process and over some time, the over-consolidation of the swelling soil is weakened and softened periodically. At the same time, the increase in moisture content causes a reduction in matrix suction in the soil and its shear strength (Bao and Ng, 2000).

Table 1 - Literature on swelling potential (after Al-Rawas *et al.*, 2000)

Author	Parameters Discussed
Altmeyer (1955)	Relates Shrinkage Limit and Linear Shrinkage both in percentage to the degree of expansion
Holtz and Gibb (1956)	Reckon the degree of expansion is related to Colloid Content, Plasticity Index, Shrinkage Limit as well as the probable expansion based on the per cent of total volume change
Seed *et al.* (1962)	Established a relationship between the percentage of clay sizes, activities and swelling potential
Chen (1965)	Incorporates laboratory and field data from the Particle Size Distribution analysis, Liquid Limit and Standard Penetration Resistance to predict similar correlations as of Holtz and Gibb which are the probable expansion and degree of expansion
Raman (1967)	Proposed classification for the degree of expansion based on Plasticity Index and Shrinkage Index
Dakshanamurthy and Raman (1973)	Proposed a classification scheme based on liquid limit alone
Van der Merwe (1975)	Developed a chart for determining expansiveness based on Plasticity Index and Clay Fractions
Snethen *et al.* (1977)	Found Liquid Limit and Plastic Index as best predictors

There is no standard definition of the term swelling potential based on Al-Rawas *et al.* (2000) meta-analysis aside from a morbid collection of articles as tabulated in table 1 and hence, it is relatively impossible to make reliable comparisons between acquired results. Despite a collection of assorted studies, it is inconclusive which particular method is accurate as a predictive or deterministic way of determining the swelling potential.

Skempton's work in 1953 is based on his previous papers in 1948 where Clay Activity was first derived by plotting the Plastic Index against Clay Fraction percentage which resulted in 3 categories of clays. Inactive clays will have Clay Activity values of under 0.75, normal clay within the range between 0.75 and 1.25, and active clay which has a value above 1.25. This classification was further refined into five categories whereby the inactive category is further split into two groups where Clay Activity values are less than 0.5 and then between 0.5 and 0.75. The active category is further expanded into two categories; first, Clay Activity value between 1.25 and 2.0, and then above 2.0. The significance of this tabulation is the inclusion of minerals' composition as shown in Table 3.

After considering all literature, the best method to determine the swelling potential is to adopt Seed *et al.*'s method which utilizes the Activity Index and Clay Fraction. This method is compatible with the conventional test performed in any JKR site laboratory. The clay fraction percentage can be acquired through the hydrometer method for Particle Size Distribution analysis and the Plastic Index through the Atterberg Limit test. The Activity Index is the outcome of the computation for the Plastic Index over clay percentage (Ozdemier and Gulser, 2017; Skempton, 1953). The scoring weightage for the work by Seed *et al*. in Illustration 1 is as follows; (0) for non-plastic, (1) for low activity, (2) for medium activity, (3) for high activity, and (4) for very high clay activity.

Activity Index = (Liquid Limit – Plastic Limit) / Clay percentage

Table 2 - Swelling Potential based on Liquid Limit (after Dakshanamurthy and Raman, 1973)

Swelling Potential	Liquid Limit (%)	Score
None	0-20	1
Low	20-35	2
Medium	35-50	3
High	50-70	4
Very High	70-90	5
Extra High	>90	6

Aside from the method proposed by Seed *et al.* (1962), the other swelling potential classification shall be based on Dakshanamurthy and Raman (1973) and value as per Table 2. Another predictive value of the clay activity to support both initial swelling potentials will be based on Skempton (1953) as per table 3.

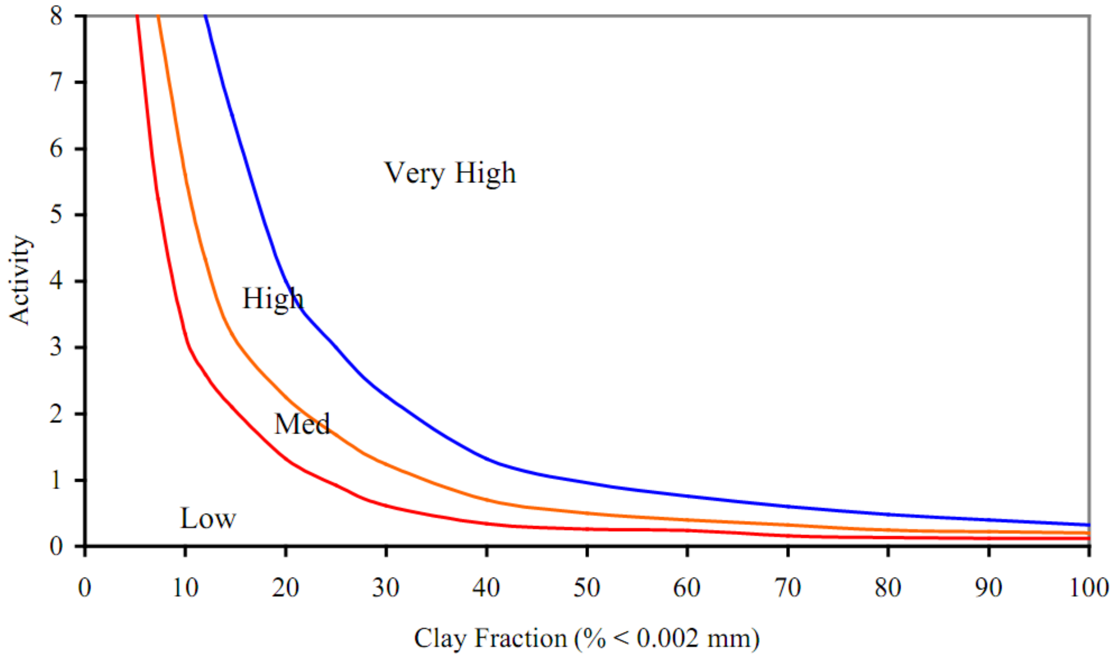

Fig. 1 - Swelling Potential Classification by Seed *et al*. (1962) after Al-Rawas *et al.* (2000)

Table 3 - Correlation between activity and mineralogy (after Skempton, 1953)

Group	Activity Range	Score	Mineralogy of Clay Fraction	
			Major	Minor
Inactive (1)	< 0.25	1	Quartz, Mica, Illite, Kaolinite, Calcite	Montmorillonite
Inactive (2)	0.5 – 0.75	2	Illite, Kaolinite	Vermiculite
Normal (3)	0.75 – 1.25	3	Illite, Kaolinite	Montmorillonite
Active (4)	1.25 – 2.0	4	Illite	Kaolinite
Active (5)	> 2.0	5	Montmorillonite	-

3. Objective and Methodology

The objective of this study is to create a spatial distribution map for expansive soils along the existing and degraded Telupid-Beluran road. This is the main road linking districts on the west coast to the central as well as the east coast of Sabah. It has been the nexus for socioeconomic growth, especially for palm oil plantations. Samples were taken from selected locations along the road as shown in Map 1 and undergo laboratory tests before being entered into GIS software for geostatistical analyses. The kriging interpolation method is used for this purpose.

Fig. 2 - Location of samples extracted at the site and basemap

3.1 Field and Laboratory Works

Soil samples were taken from the location and shall be analysed in the laboratory and undergo Particle Size Distribution analysis where the dry method via sieving shall be conducted for larger than 60µm and the wet hydrometer method shall be used to determine fine grains. For Atterberg Limits, samples will undergo a standard rolling thread test for Plastic Limit and Cassagrande apparatus for Liquid Limit. The Plastic Index is derived based on the difference between the Liquid Limit and the Plastic Limit. After samples were analysed, they shall be tabulated according to their properties and Activity Indexes and Swelling Potentials are computed.

3.2 Geospatial Analysis

GEOSTAtistical INterpolation Techniques (Kriging) (GEOSTAINT-K) utilizes the statistical properties of the measured points. The purpose is to determine the probability of certain variables occurring over an area where identifying every possible location would be impossible. Many methods are associated with geostatistics, but they are all in the kriging family (Cressie, 1988; 1990; Rivoirard, 1994 & Stein, 1999). Ordinary, simple, universal, probability, indicator, and disjunctive kriging along with their counterparts in co-kriging are available in Geostatistical Analyst (ArcGIS software).

However, simple kriging was used in this research because it can use either semivariograms or covariances (autocorrection), transformations and allow for measurement errors. Not only do these methods create prediction and error surfaces, but they can also produce probability and quantile output maps depending on the requirement.

GEOSTAINT-K is divided into two distinct tasks: quantifying the spatial structure of the data and producing a prediction (Cressie, 1988;1990; Rivoirard, 1994 & Stein, 1999). Quantifying the spatial data structure, known as variography, is fitting a spatial-dependence model to the data.

To predict an unknown value for a specific location, kriging uses the fitted model from variography, the spatial data configuration, and the values of the measured sample points around the prediction location. GEOSTAINT-K is a moderately quick interpolation method that can be exact or smoothed depending on the measurement error model. It is very flexible and allows the user to investigate graphs of spatial autocorrelation. It uses statistical models that allow a variety of map outputs including predictions, prediction standard errors, standard error of indicators, and probability (Cressie, 1988;1990; Rivoirard, 1994 & Stein, 1999). The flexibility of these methods requires a lot of decision-making and assumes the data comes from a stationary stochastic process, which is a collection of random variables that are ordered in space and/or time.

4. Results and Finding

This region encompasses various types of rock and matrix derived from melange which is argillaceous and leads to low-risk and high-risk zones of the predictive 1:50,000 swelling risk map of Beluran.

Soils of the study area underwent properties test as well as Atterberg Limits and computed results show a mixed result as tabulated in tables 4(a) until 4(e). Most of the soil properties vary from location to location and are based on averaged values of various strata. Sample 1 or S1 have relatively have a high distribution of clay and silt and which resulted in inactive clay with low swelling potential based on Seed *et al.* (1962) in Section B1 on table 4(a) and Dakshanamurthy and Raman (1973) in Section C1 of the same table. A similar pattern of distribution can be found in Samples 2, 4 and 5 but produced different outcomes where the activity indexes are found to be normal and yet resulting in low swelling potential based on B1 computation and considered to have medium swelling potential in C1 (1973). S3 constitutes highly of clay which resulted in inactive activity, low swelling potential in B1 but medium swelling potential in C1 due to higher Plastic Index value.

Soil samples in table 4(b) showcase one exception, which is S10. Despite the low Plasticity Index, the activity index is relatively high with a value of 1.55 which renders the importance of low content and the relationship in generating results based on Skempton (1953) for A1. Despite its active nature, the swelling potential remains low for both B1 and C1. In contradiction, inactive soil of S8 resulted in the medium swelling potential for both B1 and C1 computation. S7 and S9 both generated low swelling potentials normal although S7 is considered normally active clay while S9 is inactive. S11 in table 4(c) is an inactive soil with a zero score it is non-plastic and has no swelling potential. S13 is quite similar to S11 with no clay content and hence is considered inactive and non-plastic despite being grouped as low potential in C2 based on its liquid limit. S12 and S14 have low swelling potential based on Seed *et al* (1962) and medium swelling potential based on Dakshanamurthy and Raman (1973). The different rating made by Skempton (1953) elevates S14 as normal for the activity index since the value is close to the borderline. S15 is considered a very active soil since the Plasticity Index is relatively higher when the clay content is only 4.75% of the overall soil composition. Nevertheless, B1 computed value considers this soil type to have low swelling potential due to its clay fraction values and C1 reaffirms this with a relatively low Plasticity Index.

Table 4(d) exhibits a different outcome compared to tables before this which showcases S17 and S19 as inactive soil with medium swelling potentials based on values in B1 and C1 due to their high clay content. S20 is also graded as inactive soil but C1 classifies this soil to have high swelling potential while B1 placed it as medium swelling potential. S16 and S18 are active soil with low swelling potential based on Seed *et al.* (1962), while Dakshanamurthy and Raman (1973) placed these as the medium swelling potential for the former and low swelling potential for the latter. The last five samples in table 4(e) are quite consistent as these are graded to have low swelling potential based on Seed *et al.* (1962) and Dakshanamurthy and Raman (1973) with an exception for S21 which is considered to be normal swelling potential where the value is on the borderline between low and medium. All soils are considered to have normal activity except for S22 and S25 where these values are close to the borderline of being normal.

Data were entered into GIS software and interpolated via the Kriging Method; the spatial distribution of swelling soil was generated, and Maps 2, 3, 4 and 5 are generated which render distributions geographically. The Activity Index based on Skempton (1953) computed from geographically weighted regression kriging renders an interval of values which have highest at Sample S12 and progressively distributed with low values at both ends except for consistent value between S16 to S23 as shown in map 2. This finding shows that most of the soils here are normal and active clay. Map 3 renders a similar outcome based on score values. Map 2 and Map 3 capitalize on swelling potential based on the recommendation made by Skempton (1953). Map 5 generated an average value between 31.8 to 40.4 with pockets of areas which have higher and lower values. Map 4 on the other hand indicates average values between 2.42 and 2.90 where soils are believed to be either low to medium swelling potential.

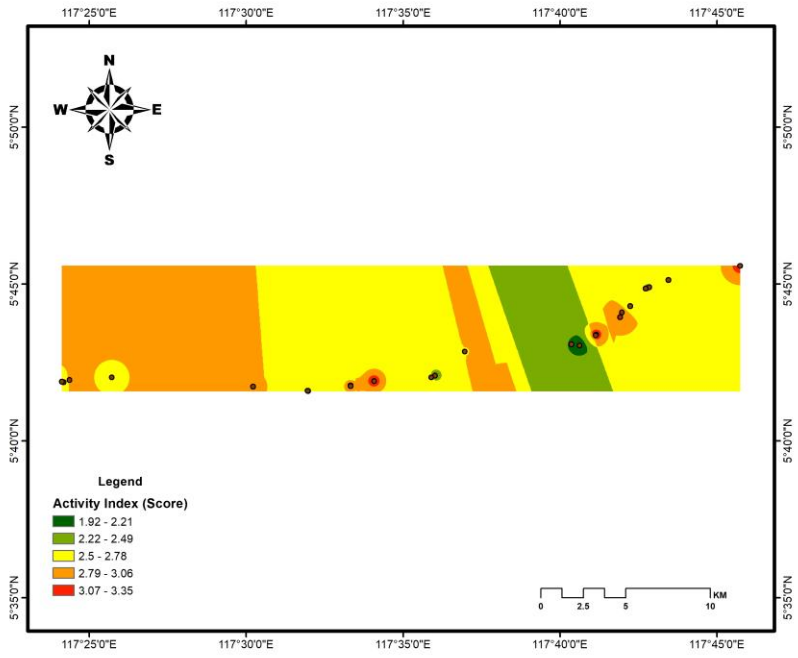

Fig. 3 - Activity score distribution

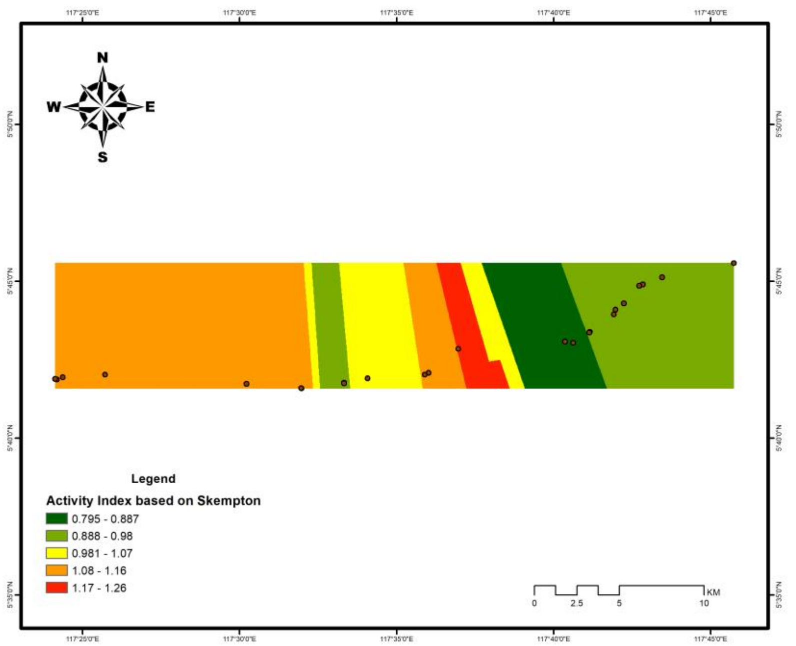

Fig. 4 - Activity index distribution

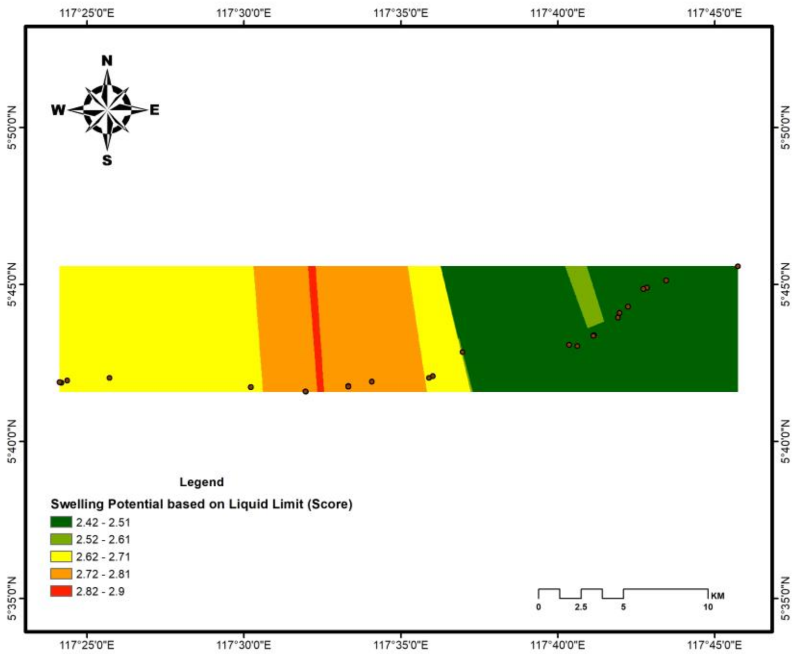

Fig. 5 - Swelling score distribution

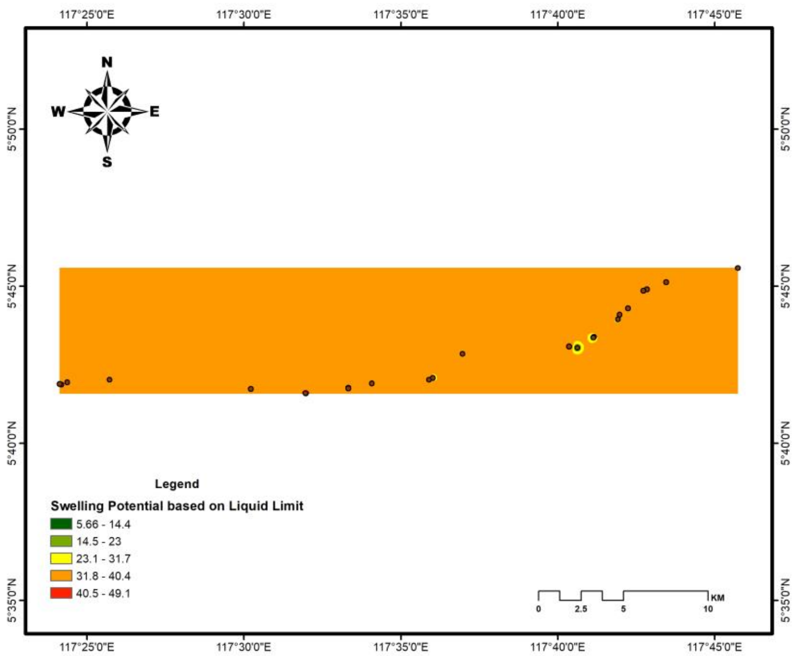

Fig. 6 - Swelling potential distribution

5. Discussion

The distribution of gravel, sand, silt and clay differs which explains the phenomenon and existence of different soil taxonomy consisting majority of either Luvisols or Acrisols, depending on the presence of the clay. Depleting clay content which is subject to weathering correlates highly with the typical Luvisols. Generally, the particle distribution construed the sampling locations as melange material which consists of various materials in a heterogeneous mixture of soil. The high clay compositions in most samples reaffirmed the argillaceous nature of the soil. Nevertheless, despite the high clay composition of clay and general link to high swelling potentials, the soil activity which is derived based on Skempton (1953) offers an inverted relationship when clay content is high but a low Plasticity Index. This demonstrates the plasticity index takes precedence when determining the activity of each soil.

Subsequently, the computation of swelling potential based on Seed *et al.* (1962) is based on clay fraction. The initial inverted relationship reduced the activity value and plot against the clay fraction. In most cases, samples yield low swelling potential when the activity is already low. Dakshanamurthy and Raman (1973) literature reckon the use of Liquid Limit as predictive properties for soil potential does indicate almost similar outcome as Seed *et al*. (1962). This may have indirectly supported the JKR standard specification for Road Works when it comes to the maximum value of 85% for liquid limit for suitable materials and having less tendency to underpredict soil swelling due to Plastic Index.

Maps which are produced show a non-existing or non-significant relationship between both activity and swelling potential. The highest swelling potential soils are located from S12 to S21 while soils with the highest activity are along the stretch between S6 and S12 until S16 as well as S19 until S24.

6. Conclusion

The study established that argillaceous soil which is predominantly clay occurs along the Telupid-Beluran road and has low to high swelling potential. It constitutes the initial step in developing a proper way to determine and classify localities which can experience swelling. Based on the present studies, it may seem to be a heuristic approach to predict accurately when missing out on clay mineral classification in determining the swelling potential.

It is reckoned that both tests by Seed *et al*. (1962) and Dakshanamurthy and Raman (1973) should be carried out to identify or justify the context of swelling potential at the construction site. Shall there be high swelling potential discovered through these tests, a subsequent affirmative test must be conducted using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) method. The introduction of Kriging Method and suggested tests provide a better context of swelling potential and plausible locations when it comes to argillaceous and melange materials which are not mentioned explicitly in the Standard Specification for Road Works. This eliminates the pretext of just a high Liquid Limit which exceeds 85% in the stipulated standard specification.

Appendix A

Table 4(a) - Processed data and swelling potential computations

Soil Properties	Site S1			Site S2			Site S3			Site S4			Site S5		
	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
PSD Details															
Gravel %	0	63	19.50	0	35	17.90	1	30	9.25	4	52	19.40	1	39	20.50
Sand %	5	32	19.75	6	48	21.60	1	30	7.25	4	40	16.80	13	58	29.17
Silt %	12	54	36.42	20	54	40.50	21	36	32.00	16	35	29.00	16	48	31.67
Clay %	2	53	24.33	3	40	20.00	35	57	51.50	5	57	34.80	0	40	18.67
Atterberg Limits															
Liquid Limit (LL)	25	41	33.58	30	46	39.13	43	46	44.00	43	47	43.00	30	47	39.00
Plastic Limit (PL)	15	23	18.50	14	21	17.38	18	20	18.75	15	18	17.00	13	20	17.33
Plastic Index (PI)	10	17	15.08	16	25	21.75	24	26	25.25	21	29	26.00	17	27	21.67
Others															
Topography	33, Moderate Hill			33, Moderate Hill			26, Low Hill			33, Moderate Hill			33, Moderate Hill		
Soil Taxonomy	Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols		
A1. Activity Index [a]	0.62 - Inactive			1.09 - Active			0.49 - Inactive			0.75 - Normal			1.16 - Normal		
A2. Score (1-5)	4			4			2			2			3		
B1. Swelling Potential [b]	Low			Low			Low			Low			Low		
B2. Score (1-5)	1			1			1			1			1		
C1. Swelling Potential [c]	33.58 - Low			39.13 - Medium			44.00 - Medium			43.00 - Medium			39.00 - Medium		
C2. Score (1-6)	2			3			3			3			3		

[a] Activity Index Based on Skempton (1953) (PI / Clay %).
[b] Swelling Potential Based on Seed *et al*. (1962).
[c] Swelling Potential based on Liquid Limit (Dakshanamurthy and Raman, 1973).

Appendix B

Table 4(b) - Processed data and swelling potential computations

Soil Properties	**Site S6**			**Site S7**			**Site S8**			**Site S9**			**Site S10**		
	Min	**Max**	**Ave**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**
PSD Details															
Gravel %	0	10	4.67	25	57	41.00	0	82	14.62	4	62	21.69	8	52	34.71
Sand %	5	8	6.00	22	63	38.25	5	34	9.54	11	63	26.69	9	56	33.64
Silt %	30	39	35.22	8	21	14.50	8	45	32.38	16	48	30.46	10	56	22.86
Clay %	37	57	51.88	3	13	6.50	0	57	43.46	3	46	21.15	0	16	8.79
Atterberg Limits															
Liquid Limit (LL)	47	63	52.56	0	0	21.00	42	51	46.14	26	34	29.33	27	31	28.80
Plastic Limit (PL)	16	21	18.00	0	0	15.00	17	21	18.57	14	19	16.25	14	16	15.20
Plastic Index (PI)	30	44	34.56	0	0	6.00	23	33	27.57	10	17	13.08	13	15	13.60
Others															
Topography	33, Moderate Hill			33, Moderate Hill			33, Moderate Hill			33, Moderate Hill			33, Moderate Hill		
Soil Taxonomy	Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols		
A1. Activity Index [a]	0.67 - Inactive			0.92 - Normal			0.63 - Inactive			0.65 - Inactive			1.55 - Active		
A2. Score (1-5)	2			3			2			2			4		
B1. Swelling Potential [b]	Medium			Low			Medium			Low			Low		
B2. Score (1-5)	2			1			1			1			1		
C1. Swelling Potential [c]	52.56 - High			21.00 - Low			46.14 - Medium			29.33 - Low			28.80 - Low		
C2. Score (1-6)	4			2			3			2			2		

[a] Activity Index Based on Skempton (1953) (PI / Clay %).
[b] Swelling Potential Based on Seed *et al*. (1962).
[c] Swelling Potential based on Liquid Limit (Dakshanamurthy and Raman, 1973).

Appendix C

Table 4(c) - Processed data and swelling potential computations

Soil Properties	Site S11			Site S12			Site S13			Site S14			Site S15		
	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
PSD Details															
Gravel %	0	0	31.00	2	65	29.56	0	0	81.00	1	29	10.33	26	56	35.25
Sand %	0	0	61.00	5	22	12.36	0	0	5.00	7	47	25.67	18	55	41.00
Silt %	0	0	6.00	10	51	28.00	0	0	14.00	19	59	36.00	14	28	19.50
Clay %	0	0	2.00	5	48	30.18	0	0	0.00	5	46	28.00	0	14	4.75
Atterberg Limits															
Liquid Limit (LL)	0	0	0.00	30	46	38.70	0	0	27.00	41	48	44.50	25	31	28.00
Plastic Limit (PL)	0	0	0.00	15	22	17.80	0	0	18.00	21	24	22.50	15	16	15.50
Plastic Index (PI)	0	0	0.00	1	27	19.80	0	0	9.00	21	24	22.00	10	15	12.50
Others															
Topography	33, Moderate Hill			33, Moderate Hill			33, Moderate Hill			33, Moderate Hill			33, Moderate Hill		
Soil Taxonomy	Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols		
A1. Activity Index [a]	0 - Inactive			0.66 - Inactive			0 - Inactive			0.79 - Normal			2.63 - Active		
A2. Score (1-5)	1			2			1			3			5		
B1. Swelling Potential [b]	Non-plastic			Low			Non-Plastic			Low			Low		
B2. Score (1-5)	0			1			0			1			1		
C1. Swelling Potential [c]	0.00 - None			38.70 - Medium			27.00 - Low			44.50 - normal			28.00 - Low		
C2. Score (1-6)	1			3			2			3			2		

[a] Activity Index Based on Skempton (1953) (PI / Clay %).
[b] Swelling Potential Based on Seed *et al.* (1962).
[c] Swelling Potential based on Liquid Limit (Dakshanamurthy and Raman, 1973).

Appendix D

Table 4(d) - Processed data and swelling potential computations

Soil Properties	Site S16			Site S17			Site S18			Site S19			Site S20		
	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
PSD Details															
Gravel %	0	60	12.00	0	18	2.71	0	5	1.00	0	2	0.60	0	0	0.00
Sand %	13	63	40.00	5	22	10.57	9	73	55.67	5	8	6.60	5	6	5.80
Silt %	27	67	42.00	23	49	41.14	22	64	36.00	40	49	450	40	46	42.20
Clay %	0	20	6.00	18	57	45.57	0	22	7.33	46	53	47.80	48	55	52.00
Atterberg Limits															
Liquid Limit (LL)	30	43	36.50	35	60	44.86	31	36	33.50	40	51	45.40	42	56	50.80
Plastic Limit (PL)	19	24	21.50	19	26	23.43	17	18	17.50	17	25	21.00	19	22	20.20
Plastic Index (PI)	11	19	15.00	24	28	26.00	24	28	26.00	23	26	24.40	23	36	30.60
Others															
Topography	33, Moderate Hill			26, Low Hill			26, Low Hill			26, Low Hill			26, Low Hill		
Soil Taxonomy	Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols		
A1. Activity Index [a]	2.5 - Active			0.57 - Inactive			3.55 - Active			0.51 - Inactive			0.59 - Inactive		
A2. Score (1-5)	5			2			5			2			2		
B1. Swelling Potential [b]	Low			Medium			Low			Medium			Medium		
B2. Score (1-5)	1			2			1			2			2		
C1. Swelling Potential [c]	36.50 - Medium			44.86 - Medium			33.50 - Low			45.40 - Medium			50.80 - High		
C2. Score (1-6)	3			3			2			3			4		

[a] Activity Index Based on Skempton (1953) (PI / Clay %).
[b] Swelling Potential Based on Seed *et al.* (1962).
[c] Swelling Potential based on Liquid Limit (Dakshanamurthy and Raman, 1973).

Appendix E

Table 4(e) - Processed data and swelling potential computations

Soil Properties	Site S21			Site S22			Site S23			Site S24			Site S25		
	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
PSD Details															
Gravel %	0	1	0.25	17	29	23.00	0	0	0.00	0	19	4.40	0	0	0.00
Sand %	50	68	56.75	27	34	30.50	13	62	45.00	25	77	52.60	0	0	57.00
Silt %	25	33	28.00	20	32	26.00	32	69	41.80	19	38	29.00	0	0	27.00
Clay %	4	21	15.00	17	24	20.50	6	18	13.20	4	26	14.00	0	0	16.00
Atterberg Limits															
Liquid Limit (LL)	35	35	35.00	0	0	30.00	28	42	33.25	30	31	30.33	0	0	30.00
Plastic Limit (PL)	18	18	18.00	0	0	17.00	16	25	19.25	9	16	13.67	0	0	19.00
Plastic Index (PI)	17	17	17.00	0	0	13.00	12	17	14.00	14	21	16.67	0	0	11.00
Others															
Topography	31, Moderate Hill, Valley			31, Moderate Hill, Valley			26, Low Hill			26, Low Hill			26, Low Hill		
Soil Taxonomy	Acrisols			Acrisols			Acrisols, Luvisols			Acrisols, Luvisols			Acrisols, Luvisols		
A1. Activity Index [a]	1.13 - Normal			0.63 - Inactive			1.06 - Normal			1.19 - Normal			0.69 - Inactive		
A2. Score (1-5)	3			2			3			3			2		
B1. Swelling Potential [b]	Low			Low			Low			Low			Low		
B2. Score (1-5)	1			1			1			1			1		
C1. Swelling Potential [c] based on Liquid Limit	35.00 - Medium			30.00 - Low			33.25 - Low			30.33 - Low			30.00 - Low		
C2. Score (1-6)	3			2			2			2			2		

[a] Activity Index Based on Skempton (1953) (PI / Clay %).
[b] Swelling Potential Based on Seed *et al.* (1962).
[c] Swelling Potential based on Liquid Limit (Dakshanamurthy and Raman, 1973).

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