An approach to locate and map swelling soils around Sohag – Safaga road, Eastern Desert, Egypt using remote sensing techniques for urban development

Salwa F. Elbeih a,*, Nehal M.A. Soliman b

a Engineering Applications Department National Authority for Remote Sensing and Space Sciences, Cairo, Egypt
b Mineral Resources Department National Authority for Remote Sensing and Space Sciences, Cairo, Egypt

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Abstract The detrimental consequences of swelling soils are most apparent in arid and semi-arid regions. Sedimentary clays are mixtures of illite, kaolinite and some montmorillonite. There are various soil types liable to swell such as shale, mudstone, siltstone and marl due to the presence of Smectite group in these soils. Large volume changes of these types of soils can cause extensive damages to civil engineering infrastructures; roads, airport pavements, pipelines and shallow foundations. A number of localities in Egypt are well-known by the presence of swelling soils. Sohag – Safaga highway in the Eastern Desert of Egypt is considered to be an investable transportation road and one of the most important lateral connections between Upper Egypt and the Red Sea area. The study area is located in a buffer zone of 25 km from both sides of the highway. This area is believed to be more influenced by the road and could be fully utilized to share in developing areas in the road vicinity. The research objectives are to use recent ASTER satellite imageries with the aid of field samples to map different swelling clay minerals and compare between the different sensors accuracy in locating them within the buffer zone. Certain engineering measures should be considered to enable construction over these types of swelling soils. The results confirmed the presence of montmorillonite in this buffer zone and in the 5 km buffer around the road which represents a hazard especially for the future planned projects within this area.

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1. Introduction

Under the ever increasing rates of population in Egypt within the Nile Valley and Delta, it became essential in front of decision makers to establish and extend new communities in the desert areas. This extension is vital in order to sustain the increasing...
population, now exceeding 88 million, concentrated in less than 8% of its land area (SIS, 2015). Low desert zones, located between the Nile flood plain and the Limestone plateau in the Eastern Desert, are the most favorable areas for these extensions. Most of these areas are occupied by marine Pliocene clay deposits (Youssef, 2008). Aligned with the governmental emphasis on developing Upper Egypt governorates, transverse roads are considered one of the most important methods to conduct various developmental projects in these regions. A number of localities in Egypt are well-known by the presence of swelling soils such as; Nasr – City, Cairo – Suez Road, El – Fayoum, Kom Ombo, Aswan, New Valley and El – Sadat City. Sohag – Safaga highway and the buffer area around it (Fig. 1) is considered to be a development investible transportation corridor and one of the most important lateral connections between Upper Egypt and Red Sea and its ports. The area east of Sohag (the study area) suffers from the presence of Pliocene clay that is characterized by its swelling nature (Youssef, 2008).

Swelling soils cause many problems in the civil engineering industry where they swell considerably on absorption of water from outside and shrink on its removal. This phenomenon is exhibited to a very marked degree only in certain clayey soils (Singh, 1967). The detrimental consequences of swelling soils are most obvious in arid and semi-arid areas since water content near the surface is usually kept low by evaporation (Peck et al., 1980). The presence of swelling soils on the surface is probably an indication for the unknown subsurface swelling soils that can only be identified using boring. Occurrence of swelling soils in construction sites has serious consequences on planning, design, construction, maintenance, and the overall performance especially of lightweight engineering infrastructures. In some clays and shales, swelling caused by reduction of stress, is so great that it disrupts roadways or structures. If swelling is restricted by construction, extremely large forces may develop and soils are said to be swelling (Peck et al., 1980). The large volume changes can cause extensive damages to civil engineering infrastructures; roads, airport pavements, pipelines, shallow foundations and light weight structures. Foundations over swelling soils may cause damages to the buildings over which they are constructed. Problems related to foundations on swelling soils include: heaving, cracking and breakage of pavements, building foundations, slab – on grade members, and channel and reservoir linings.

Expansive soils owe their characteristics to the presence of swelling clay minerals. When wetted, the clay minerals absorb water molecules and expand. On the other hand, when clay dries it shrinks and it leaves large voids in the soil. Swelling clays can control the behavior of virtually any type of soil if the clay is more than about 5% by weight. Soils with smectite clay minerals (montmorillonite) exhibit the most considerable swelling properties (Youssef, 2008). There are various soil types liable to swelling, such as shale, mudstone, siltstone and marl due to the presence of swelling clay minerals. The type of clay mineral plays an important role in the determination of heave in swelling soils. Illites, Kaolinite and montmorillonite are the main clay minerals where the latter possesses the ability to swell the most (Gromko, 1974). Sedimentary clays are mixtures of the pre-mentioned clay minerals and most changes that cause engineering problems take place at depths of less than 10 ft (Gromko, 1974). The amount of heave depends upon a number of parameters including thickness of clay strata, overburden, water table depth, amount and activity of clay, rate of evaporation, frequency of rainfall, leakage of water and sewer lines and soil density (Gromko, 1974).

Figure 1  Location map of the study area overlaid a base map showing the main governorates and cities surrounding the study area.
Remote sensing is considered to be one of the advanced techniques used in hazards identification. Although using satellite imagery, a certain proportion of soil coverage response would be masked (i.e. in or near urban areas, or under thick and dense vegetation conditions); this would open the door for low – cost, large – scale mapping of clay mineralogy leading to swelling of soil. Chabrillat et al., 2002 found that it is possible to distinguish between the spectral response of three indicator clay minerals; smectite, illite, and kaolinite based on airborne sensor data. The use of satellite images during the early stages of mineral exploration has been very successful in pointing out the presence of minerals such as smectites and kaolinite, important in the identification of hydrothermal alterations (Chabrillat et al., 2002). These minerals are key to the soil properties (swelling or non swelling) and their identification from space makes remote sensing a good tool in the characterization of soils in terms of swelling potential. It is possible to distinguish between the spectral response of three swelling potential indicator clay minerals i.e. smectites, illites and kaolinites based on airborne sensor data (Kariuki et al., 2004).

With improving of the spectral resolution of spaceborne hyperspectral sensors such as the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), the capacity to resolve small spectral features from remote sensing in the future for such soil property mapping is becoming a reality (Youssef, 2008). ASTER is an imaging instrument on board the Terra satellite of NASA’s Earth Observing System (EOS) (launched 19 December 1999). It is designed with three bands in the VNIR (visible and near-infrared) spectral range with a wavelength ranging from 0.52 to 0.86 micrometers with a 15 m spatial resolution, six bands in the SWIR (shortwave infrared) spectral range with wavelength ranging from 1.60 to 2.43 μm with a 30 m spatial resolution, and five bands in the TIR (thermal infrared) spectrum range with a wavelength ranging from 8.125 to 11.65 μm with a 90 m spatial resolution. The VNIR and SWIR bands have a spectral resolution in the order of 10 nm that is sufficient for clay mineral mapping (Van der Meer, 1999). ASTER satellite image libraries are used to map different clay minerals and compare between the different sensors accuracy in locating these clay minerals based on the spectral library.

Chabrillat et al. (2002) used data sets from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the Hyperspectral Mapper (HyMap) for identification and mapping of swelling soils. Using a matched filtering algorithm, maps of exposed clay material were produced. Spectral discrimination and identification of various clay minerals such as smectite, illite, and kaolinite, in decreasing order of swelling potential hazard, were possible. The comparison of the results from the two sensors showed that higher spatial resolution provided purer image endmembers in more heterogeneous sites, but did not exhibit more endmembers and did not identify new natural outcrops that a lower spatial resolution data set would miss in a homogeneous terrain. Kariuki et al., 2004 established the combined use of spatial and spectral resolutions of Landsat 7 ETM+ data in identification and location of soils susceptible to swelling. The spectral information of Landsat 7 ETM+ was useful to establish differences in the signature of heavy vegetation and scarce vegetation and to some extent the hydroxyl. The results were improved by the use of higher spatial resolution panchromatic band 8 (with a spatial resolution of 15 m), to establish the micro topography difference in the swelling soils. (Bourguignon et al., 2007) detected and mapped shrink swell clays in southwest France using ASTER imagery using the six spectral bands in the short wave infrared domain, particularly wavelengths between 2.145 and 2.43 μm.

Youssef (2008) used Landsat 7 images and applied several data enhancement techniques using Univariate and Multivariate statistics. He used Minimum Noise Fraction (MNF) and Principal Component Analysis (PCA) and then supervised classification was used to test their effectiveness and to establish differences between different deposits and detect the Pliocene clay deposits. Van der Meer (1999) explained the reflectance spectra for three groups of the clay minerals (Fig. 2). The spectrum of montmorillonite is typical for water – rich mineral, showing strong absorption bands near 1.4 and 1.9 μm, and an additional band near 2.2 μm. Absorption features of illites are generally broader and less well defined where it shows broad water absorption bands near 1.4 and 1.9 μm, and additional Al-hydroxyl features at 2.2, 2.3 and 2.4 μm. Illite and muscovite have absorption bands near 2.35 and 2.45 μm, which are lacking in the montmorillonite spectrum. Kaolinite has well-known double absorption near 2.2 μm, and an additional hydroxyl feature at 1.4 μm. The main objective of this research paper is to use ASTER satellite images with the aid of field collected samples to map and locate the different clay minerals and compare between the different sensors accuracy in locating these clay minerals.

Constrained Energy Minimization (CEM) mapping technique was used for this purpose.

2. Regional setting

2.1. Study area

The study area is located in the Eastern Desert of Egypt where it occupies a large district between the River Nile Valley and the Red Sea and covers four Governorates (Fig. 1). Along the River Nile Valley, these governorates are, from north to south; Assuit, Sohag, and Qena. It also includes a large sector of Red Sea Governorate overlooking the Red Sea Coast. The road is connecting these four governorates (Fig. 1). Sohag – Safaga new highway is considered to be a development investible transportation road and one of the most important lateral connections between Upper Egypt and the Red Sea and its ports. It begins from Sohag governorate and extends toward the east in the direction of the Red Sea until it meets with Qena – Safaga road. The study area is located in a buffer zone of 25 km from both sides of the road (NARSS, 2010; Elbehil et al., 2011). This buffer area was chosen to cover the proposed development activities previously suggested around the road. This buffer area is believed to be more influenced by the road and in the same time includes a number of natural resources and minerals that could be fully utilized to share in developing the areas in the road vicinity. As shown in Fig. 1, the study area is located between latitudes 25° 57’ 37.5” and 27° 34’ 57.0”N and longitudes 31° 0’ 37.7” and 34° 9’ 7.6” E with an area of about 25513 km².

Climatologically, the study area is distinguished by the scarcity of rain and relatively high moisture content. In
November 1994, the area received about 25 mm/day where floods struck the Red Sea and the Nile Valley provinces and caused serious damage (EMA, 2000) and in January 2010, floods struck the Western side of the study area. Rainfall over the study area is very limited and variable (Diab et al., 2002; Abu El Ella and Abdel Mogeeth, 1993). Rainfall data were compiled from nine meteorological stations within and around the study area for the period from 1968 to 2002. Some parameters contributing to the expected heave due to the presence of swelling soils in the study area are shown through some field photos in Qena and Sohag development areas as shown in Fig. 3 (NARSS, 2010).

2.2. Geological and structural description

Geologically, the study area was divided into three main units; Basement rocks, Cretaceous and Tertiary sediments and Quaternary sediments (Fig. 4) (Said, 1990).

2.2.1. Basement rocks

Basement rocks are composed essentially of pan-African arc assemblage and comprise gneisses and migmatites, metasediments, ophiolitic mélangé calc-alkaline metavolcanics, mafic intrusions, tonalite, granodiorite, younger volcanic, Molasse sediments, post tectonic granites and trachyte plugs and sheets (refer to the geological map Fig. 4 scale 250,000). All of these rock units are dissected by numerous mafic and felsic dykes. On the other hand these basement rocks are unconformably overlain by the Phanerozoic sediments, at the west (Cretaceous rocks) and east (Miocene rocks).

2.2.2. Cretaceous and tertiary sediments

The stratigraphic section, in the study area, is composed of cretaceous – Lower Tertiary rock units, which are found to be unconformably overlain by one or more of much younger surficial deposits, (Pliocene and Quaternary conglomerates, sandstones and gravel terraces). These rock units are recognized and mapped in the field, they are illustrated and described from oldest to youngest as follows: The Nubia Formation, The Duwi Formation, The Dakhla Formation and Tertiary formations (Tarawan, Esna, Thebes and Issawia formations).

2.2.3. Quaternary and recent sediments

These sediments include horizontal Pleistocene reefal limestone associated with wave cut terraces with beach gravels coalescing alluvial fan deposits.

2.2.4. Dykes and veins

Phanerozoic sediments are traversed by a number of dykes (general trends NE–SW, NW–SE, N–S and rarely E–W). They can be classified into acidic, intermediate, basic, alkaline and ankerite dykes) and veins (subdivided into three main types: quartz, pegmatite and carbonate veins).

2.2.5. Structural elements in the study area

The area possesses a complex structural history. Structures are clearly observed around Meatiq dome, Wadi Atalla, Wadi Hammamat, Wadi Queih and Bir Um Fawakhir. The area was subjected to a normal, wrench and thrust faults in addition to strike-slip shear zones. The normal faults are older and were formed at different phases. The microlinears are conforming to the major structures (Said, 1990).

3. Materials and methods

3.1. Satellite data: ASTER images

The analysis of digital data was based on the combination of remote sensing and GIS (Geographical Information Systems)
Figure 3  Field photos illustrating some features that contribute to the amount of expected heave of swelling soils: (A) Shallow water table depth in Qena Governorate new development areas; (B) Thickness of the fine sediments as an indication of the flashflood strength in Qena Governorate new development areas; (C) Some plants as an indication of shallow groundwater in Sohag Governorate new development areas (NARSS, 2010).

Figure 4  Geological map of the study area (Modified after EMRA Geological Map of Egypt scale 1:250,000: sheets: Gebel El-Urf: 1983, Hurgada. 2005, Wadi Qena: 1983 and Quseir: 1992).
using ESRI Arc GIS 10 and ENVI 5.1 as primary tools. Remote sensing data were interpreted using ASTER satellite images. The ASTER instrument is based on the NASA Terra satellite, which is part of the Earth Observing System. It provides high-resolution images of various bands from visible to infrared wavelength in different resolutions (Table 1). The swath width of each scene averages 60 km × 60 km. ASTER data analyzed in this work were obtained from the Earth Remote Sensing Data Analysis Center (ERSDAC) Tokyo, Japan at the 1B processing level. The radiometric and geometric coefficients are corrected. A total of sixteen ASTER images acquired in 2006, 2007 and 2008 (with 0% cloud cover) were used with their spectral and spatial resolutions of the visible Near Infrared and Short wave Infrared bands shown in Table 1.

3.2. Preparing ASTER images for mapping clay minerals and alteration zones

The methodology adopted for preparing the images of the study area for processing includes the following steps (ASTER Users Handbook GIS Portal, 2009; Thome et al., 2001). In the first step, the DN (digital numbers) of the single ASTER channels were converted to spectral reflectance as follows.

3.2.1. DN conversion to spectral radiance

Data used in this research is ASTER L1B data (version 3.0), were radiometrically calibrated to reflectance. Only VNIR and SWIR bands were used. The nine bands were resampled to 15 m. DN were converted to spectral radiance through the following equations:

\[ L_{rad,j} = (D_{N,j} - 1) \times UCC_{j} \]  

where, \( L_{rad,j} \) is ASTER spectral radiance at the sensor’s aperture measured in a wavelength \( j \); \( j \) is the ASTER band number; \( D_{N,j} \) is the unitless DN values for an individual band \( j \); UCC \( j \) is the Unit Conversion Coefficient (W m\(^{-2}\) sr\(^{-1}\) μm\(^{-1}\)) (ASTER Users Handbook, Abrams and Hook, 1999):

\[ L_{rad,j}(C) = A_{j} \times L_{rad,j} + B_{j} \]  

where, \( L_{rad,j}(C) \) refers to the re-calibrated spectral radiance, \( A \) and \( B \) are re-calibration coefficients for a band \( j \).

<table>
<thead>
<tr>
<th>Table 1 Spatial and spectral resolutions of the ASTER images in the VNIR and SWIR.</th>
<th>Band label</th>
<th>Spectral range (μm)</th>
<th>Spatial resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible and near infrared (VNIR)</td>
<td>B1: VNIR_Band1</td>
<td>0.52–0.60</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>B2: VNIR_Band2</td>
<td>0.63–0.69</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>B3N: VNIR_Band3N</td>
<td>0.78–0.86</td>
<td>15 (Nadir view)</td>
</tr>
<tr>
<td>Shortwave infrared (SWIR)</td>
<td>B4: SWIR_Band4</td>
<td>1.60–1.70</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B5: SWIR_Band5</td>
<td>2.145–2.185</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B6: SWIR_Band6</td>
<td>2.185–2.225</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B7: SWIR_Band7</td>
<td>2.235–2.285</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B8: SWIR_Band8</td>
<td>2.295–2.365</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B9: SWIR_Band9</td>
<td>2.360–2.430</td>
<td>30</td>
</tr>
</tbody>
</table>

3.2.2. Spectral radiance to TOA (top-of-the-atmosphere) reflectance

ASTER at-sensor reflectance (\( \rho_{\text{TOA},j} \)) for a specific band \( j \) is calculated using the standard Landsat equation as:

\[ \rho_{\text{TOA},j} = \frac{\pi \cdot L_{rad,j} \cdot d^2}{E_{\text{SUN},j} \cdot \cos(h)} \]  

where \( \rho_{\text{TOA}} \) is the unitless planetary reflectance, \( L_{rad} \) is the spectral radiance at the sensor’s aperture, \( d \) is the Earth–Sun distance in astronomical units, \( E_{\text{SUN}} \) is the Mean solar exoatmospheric irradiances, \( \lambda \) is the Wavelength, which corresponds to the band number \( j \) and \( h \) is the Solar zenith angle in degrees (zenith angle = 90 – solar elevation angle), which is found in the ASTER header file.

3.3. Performing the mosaic

For each of the sixteen ASTER images, a spectral subset is performed on a band by band base for each of the nine bands (visible and visible near infrared). A subset is performed on each image and the image is rotated based on the rotation angle of the satellite, and to get the true North direction of the image. Gram Schmidt sharpening is performed on each of the SWIR bands (bands from 4 to 9) to change their spatial resolution from 30 to 15 m. After performing the Gram Schmidt sharpening, a difference in pixels and rows between VNIR and SWIR appears so the difference is cut between them for each band at each image, to obtain the same pixel and row numbers. Using a buffer zone of 25 km, each band is cut and subset for the sixteen images using the buffer zone around the road from both sides (which is believed to be the area influenced by the road).

A mosaic is obtained for each image with its neighboring one by adjusting the stretch, feathering and deciding the fix/adjusted image based on the quality of the images. It is preferred to be done strip by strip or path by path as they might have the same acquisition date and same sun angle and other parameters which make the mosaic simpler. The area was divided into many strips and the mosaic was executed on them strip by strip. A full mosaic is made for each band of each image at that strip (producing new images having the same band from all of them), then a band base mosaic was created (example: band 1 for all images, band 2 for all images etc.). Fig. 5 shows the gray scale mosaic for the whole study area.

3.4. Spectroradiometer field measurements

During a field trip in 2011, 40 disturbed soil samples from about 1.0 to 1.5 m depth open pits were collected through a stratified random sampling technique. The sample locations are representative of all rock types within the study area and are located inside the buffer area of 25 km and an additional buffer of 5 km around the road (Fig. 6). Samples were chosen to evaluate the spectral reflectance of the selected ASTER band combination through building the spectral library for the study area based on the spectral signatures measured. In addition, they were used for further calibration to support detailed remote sensing analysis. Soil reflectance spectra were obtained using the ASD field spec full range spectrometer (http://www.asdi.com) that covers the spectral range of
350–2500 nm wavelength of the electromagnetic spectrum. Measurements were done on small portions of air-dried soil samples quartered from the whole sample to ensure representativeness. Time spent to acquire the reflectance spectra of soil samples was incomparable with that which will be spent for the conventional geotechnical engineering tests that will take several weeks' time.

3.5. Mapping of clay minerals and alteration zones

The alteration of hydrothermal deposits may result in an extension from tens of centimeters to tens of kilometers. It is generally represented by the spatial arrangement that is divided from the central potassic zone to the outward direction of the phyllite or phyllic (sericitic) zone, argillite or argillic zone, and propylitic zone in that order (Lowell and Guilbert, 1970). These zones are characterized by an assemblage of minerals that exhibit distinctive spectral absorption features.

In the phyllite or phyllic zone, mainly quartz, sericite, and pyrite exist, but sericite is predominated. The absorption of sericite (muscovite) is strongest at a wavelength of 2.2 \( \mu \text{m} \) (ASTER band 6). In the argillite or argillic zone, kaolinite and montmorillonite are present, whereas pyrophyllite and alunite are abundantly formed in advanced argillic zones. With the exception of montmorillonite, these minerals display absorption features near 2.16 \( \mu \text{m} \) (ASTER band 5). Calcite, chlorite, and epidote mainly exist at the propylitic zone. These minerals have the strongest absorption features at the 2.33 \( \mu \text{m} \) (ASTER band 8).

In the present study, a new spectral library was established; derived from the signatures taken from field samples to identify montmorillonite from the VNIR/SWIR surface reflectance data. Montmorillonite has special characteristics of swelling soil toward construction, spectral absorption and reflectance as shown in Fig. 7.

Mapping surface mineralogy using remote sensing sensors provides an opportunity to improve initial steps of exploration. ASTER sensor presents unprecedented opportunities for mineral exploration. Several authors used different remote sensing techniques designated for target detection, such as Constrained Energy Minimization (CEM) (Chang and Heinz, 2000; Settle, 2002; Chang and Wang, 2006), Principal Component Analysis (PCA) (Crósta and Moore, 1989; Loughlin, 1991; Rokos et al., 2000; Crósta and Filho, 2003), band ratios (Sultan and Arvidson, 1986; Rokos et al., 2000; Xu et al., 2004) or a contribution of band ratios and PCA (Zhang et al., 2007).

3.6. Constrained energy minimization (CEM)

In 1993, Harsanyi proposed the constrained energy minimization (CEM) technique that has been developed to solve the typical adaptive beam-forming problem in signal processing (Resmini et al., 1997; Farrand and Harsanyi, 1997). Since then, it has become one of the most widely used techniques for target abundance mapping. CEM performs a matched filtering (MF) of hyperspectral/multispectral images. It then linearly constrains a desired target signature while minimizing other unknown signatures. The only required knowledge is the training target spectra to be provided as user end members.

Mapping was applied using the spectral signatures of the different samples obtained during the field trip. Fig. 8 is a
graphical representation of the spectral signatures of the samples obtained from spectro-radiometrical study of the samples taken from the field. The results of CEM appear as a series of gray scale images, one for each selected endmember (one sample). The default stretch setting provides good visibility for small features. Thresholding was carried out on the montmorillonite images; density slicing was carried out to show the places of montmorillonite with maximum intensity.

CEM technique performed well and identified areas of hazardous clay minerals. In other words, it is problematic to enhance the target spectra while minimizing background “energy” using CEM when there is no apparent difference between the target and background spectral signatures.

3.7. Detecting hazardous sites using modeling

Using Arc GIS V. 10.1, a model is repaired within the Model Builder. Thematic layers required for determining hazardous areas from montmorillonite clay mineral are prepared from the results of CEM. An overlay suitability model (Fig. 9) was developed to map and locate the most hazardous areas inside the buffer zone of the road depending on a number of governing factors; the areas with mapped montmorillonite
and a 5 km buffer zone polygon around the road. The 5 km buffer intersects with the mapped montmorillonite area. This 5 km buffer chosen within the predefined 25 km buffer is a zone directly influencing the road.

4. Results and discussion

4.1. Interpretation of the processed ASTER data

Fig. 10 shows the ability of the CEM technique to deal with mixed background spectra. CEM technique performed very well and indentified areas of hazardous clay minerals. Most of the montmorillonite clay minerals are concentrated along the Nile Valley but the rest of the regions are distributed inside and within wadis of the Eastern side of the study area (overlooking the Red Sea) and in Wadi Qena in the middle section. CEM result can be used for alteration zone mapping with less field visits especially in inaccessible areas. This is because the result is much closer to the real conditions in the study area and it also matches the geological and stratigraphic description (Fig. 4).

4.2. Hazards urban development

As a result of the applied suitability model (Fig. 9), hazardous area of swelling soil in the 5 km buffer zone of the study area was obtained (Fig. 11). This 5 km buffer zone is considered to be the area most liable to urban development around the road.
Through the intersection of the two layers (the 5 km buffer and montmorillonite location areas), an output map is obtained that precisely locates these hazardous areas in the 5 km buffer zone (Fig. 11). These hazardous areas are overlaid over the proposed development projects areas within the study area (obtained from the National Center for Planning Governmental Land Uses in Egypt). It could be observed that some of these hazardous areas intersect with the proposed development areas for urbanization extension, which represent a great advantage for decision and policy makers for future planning.

5. Conclusions and recommendations

In the current study the effectiveness of using ASTER satellite images for surface mapping of swelling soils was demonstrated. With the applied methodology of the CEM, it was possible to map the distribution of the montmorillonite clay and to relatively locate them with the aid of 40 rock and soil samples collected from the study area. These samples were analyzed using the spectroradiometer. Possible hazardous sites from problematic clay minerals are present in the 5 km buffer zone around Sohag – Safaga highway. It is recommended to change the road path at the sections that have swelling soils intersecting with the proposed development areas where it will be so dangerous for any future construction projects on these parts (Fig. 11).

These hazardous locations need to be further studied using field and laboratory analysis in order to investigate their risk degree for construction purposes. Geotechnical soil analysis such as the free-swell test, colloid content, plasticity index and shrinkage limit is essential for a direct determination of the swelling potential of these clays. It is recommended to geotechnically analyze the samples obtained from the field and determine their swelling properties and also analyze using X-ray diffraction methods. In addition it is suggested to acquire hyperspectral data to be used for accurate mapping of clay minerals and alteration zones.

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