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Data Descriptor

Experimental Data on Maximum Swelling Pressure of Clayey Soils and Related Soil Properties

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Abstract: Clayey soils exhibit significant volumetric changes in response to variations in water content. The swelling pressure of clayey soils is a critical parameter for evaluating the stability and performance of structures built on them, facilitating the development of appropriate design methodologies and mitigation strategies to ensure their long-term integrity and safety. We present a dataset comprising maximum swelling pressure values from 759 compacted soil samples, compiled from 16 articles published between 1994 and 2022. The dataset is classified into two main groups: 463 samples of natural clays and 296 samples of bentonite and bentonite mixtures, providing data on various types of soils and their properties. Different swelling test methods, including zero swelling, swell consolidation, restrained swell, double oedometer, free swelling, constant volume oedometer, UPC isochoric cell, isochoric oedometer and consolidometer, were employed to measure the maximum swelling pressure. The comprehensive nature of the dataset enhances its applicability for geotechnical projects. The dataset is a valuable resource for understanding the complex interactions between soil properties and swelling behavior, contributing to advancements in soil mechanics and geotechnical engineering.

Keywords: expansive clay; bentonite; soil expansion; swelling pressure; soil index properties

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1. Summary

This study addresses the critical need for comprehensive and accessible data on the maximum swelling pressure of expansive soils, which may pose significant geohazards causing damage to civil infrastructure [1]. Understanding the behavior of clay soils under varying environmental conditions is crucial to designing secure and resilient civil infrastructure [2,3]. The dataset compiled from experimental studies on naturally occurring and laboratory-engineered clayey soils provides an invaluable resource for researchers and practitioners working on expanisve soils.

The dataset is derived from experimental studies on naturally occurring and laboratory-engineered clayey soils. Data are collected from articles and organized into 16 groups, each corresponding to a specific study. This dataset covers a variety of soil types and conditions, with swelling pressure measured using standard and modified oedometer devices. Furthermore, it includes essential soil index properties such as specific gravity (G_s), unit weight (γ), Atterberg limits (w_L, w_p, I_p), initial water content (w_i), and void ratio (e).

This dataset is a valuable tool for researchers and professionals in geotechnical, civil, geological, and geoenvironmental engineering. It has the potential to aid in the development of predictive models and advanced risk assessment strategies, ultimately contributing to safer and more efficient civil engineering practices. The adherence to the FAIR guiding principles ensures its accessibility and usefulness for a broad audience.

2. Research Background

The data presented are derived from various articles. Researchers interested in a more in-depth understanding of specific aspects of the data can refer to the references provided. In this section, we provide a brief description of each experimental study used to compile the dataset. It should be mentioned that only the maximum swelling pressure values of soil samples and the relevant soil properties were extracted from the articles cited.

Basma et al. [4] analyzed compacted clay soils in northern and central Jordan to measure their swelling pressure using various methods. These methods included the zero swelling test, swell-consolidation test, restrained swell test, and the double-oedometer swell test. The zero swelling test was performed by applying a 6.9 kPa load to a compacted specimen, followed by adding water and increasing pressure to prevent swelling. Swelling pressure was defined by the total load required to prevent any further swelling of the specimen. The swell-consolidation test involved allowing a wetted sample under a 6.9 kPa load to swell fully before conducting a standard consolidation test. The restrained swell test calculated the swelling pressure by the ratio of the maximum expansion to the initial height of the specimen, with no expansion at the defined pressure. The double-oedometer test used two identical specimens, one loaded incrementally and the other inundated without load, to measure swelling pressure based on the equilibrium between the percent settlement of the first and the percent swell of the second specimen.

Komine and Ogata [5] examined compacted commercial bentonite samples produced at the Tsukinuno mine in Japan. The test apparatus is designed to measure the swelling pressure of compacted bentonite by applying an initial vertical pressure of 1.96 kPa to the sample and supplying distilled water from below. The apparatus ensures minimal deflection and deformation of the sample, indicating that the change in volume during water uptake is negligible. The relationship between swelling pressure and the time from the onset of the water supply was recorded. Post-experiment analysis confirmed that the samples reached full saturation at the end of the study.

Ergüler [6] determined swelling properties of untreated natural soil samples from Ankara in Turkey, known as "Ankara Clay", using ASTM [7] standard procedures [8].

Rao et al. [9] studied 10 remolded expansive soil samples from Andhra Pradesh state in India. The index properties of the soils were obtained using ASTM procedures. The swelling potential and swelling pressure of soils were determined by the swell-consolidation method, which is a free inundation method. This involved saturating soil samples under a specified surcharge pressure, observing volumetric changes, and taking dial gauge readings until equilibrium swell was reached. The swelling pressure was then calculated using the e-log p-curve method, where the pressure corresponding to the initial void ratio was determined [10].

Villar and Lloret [11] analyzed the swelling pressure of FEBEX bentonite. The bentonite blocks were first prepared by uniaxial compaction of the granulated clay with its hygroscopic water content, at dry densities close to 1.7 $Mg\,m^{-3}$. The swelling pressure test was conducted using oedometer frames and cells designed to accommodate the high pressures expected from the swelling bentonite. The test involved saturating the bentonite samples from the bottom upward, closely monitoring the process with a dial gauge to control swelling by applying loads. They maintained the volume of the sample constant during saturation, with the swelling pressure determined when no further strain was observed under a constant load for at least 24 h.

Komine et al. [12] examined the influence of seawater on the swelling characteristics of five different bentonites: Kunigel-V1 from Japan's Tsukinuno Mine, Volclay from Wyoming in the USA, Kunibond from Japan's Dobuyama Mine, Neokunibond from Japan's Kawasaki-cho Mine, and MX-80 also from Wyoming. The experiments used distilled water and artificial seawater as solutions applied to bentonite specimens. Swelling pressure and deformation experiments were conducted using a self-constructed constant volume test apparatus made of corrosion resistant 316 L stainless steel. The vertical swelling deformation of the bentonite samples was restricted and the minute vertical deformations were precisely measured using a linear variable displacement transducer with a resolution of 0.001 mm. Vertical swelling pressure was measured by the load transducer and the test period was one week.

Schanz and Tripathy [13] examined the swelling pressures of compacted bentonite samples from Bavaria, Germany. They utilized an oedometer setup, specifically designed to measure swelling pressures under isochoric conditions, a method where the specimen's volume remains constant during water saturation. The samples, varying in dry densities and with an initial water content of 9.9%, were saturated with distilled water and the resulting swelling pressures were measured using a load cell integrated into the oedometer device.

Baille et al. [14] investigated the swelling pressures and the one-dimensional compressibility behavior of compacted saturated bentonite from Bavaria, Germany. They designed and manufactured a high-pressure oedometer device capable of measuring swelling pressures and further loading clay specimens to large pressures. This device, featuring a force transducer enabled measuring swelling pressures under isochoric conditions. In addition, the setup was equipped to monitor the compressibility behavior of the bentonite samples under various pressure conditions.

Çimen et al. [15] analyzed disturbed clay samples from various regions in Turkey. The physical properties of these clays, such as mineral content and plasticity, were characterized using X-ray diffraction and standard ASTM tests. The samples were prepared by oven-drying, crushing, and sieving, followed by mixing with distilled water to achieve various initial water contents. Compaction was performed using a standard Proctor hammer and free-swell tests were conducted in an oedometer cell, according to ASTM [16], allowing the samples to swell freely under seating pressure. The swelling pressure was determined as the pressure required to bring the sample back to its initial height.

Cui et al. [17] studied the swelling pressure and deformation characteristics of GMZ bentonite–sand mixtures, using bentonite from Gaomiaozi, Inner Mongolia, China. They employed a WG triple high-pressure consolidometer apparatus for swelling pressure tests. The apparatus included a confining ring to prevent lateral deformation of the specimens, which were cut to a standard size and placed between two porous stones. Swelling pressure was determined by adding weight to the loading ram as the specimen absorbed water and swelled, until the dial gauge returned to its initial reading. The maximum allowed soil strain was 0.01 mm. The maximum swelling pressure was obtained when the dial gauge reading remained constant for 24 h.

Schanz and Al-Badran [18] conducted a detailed analysis of the swelling pressure of Gaomiaozi bentonite (GMZ01). They used both one-step and multi-step wetting swelling pressure tests under constant volume conditions, using specimens with five different dry densities ranging from 1.15 to 1.75 $\mathrm{Mg\,m^{-3}}$. The tests were carried out in a UPC Isochoric cell, equipped with a load cell to measure swelling forces. This setup utilized both the axis-translation technique (ATT) and the vapor equilibrium technique (VET) for suction control. Distilled water was used for wetting.

Hakami and Seif [19] assessed the swelling characteristics of clayey soil samples from the Rabigh sabkha area in Saudi Arabia. The study involved drilling boreholes and collecting 25 undisturbed soil samples, which were then subjected to various tests to determine their physical, chemical, mineralogical, and mechanical properties. These tests were carried out following ASTM standard procedures. The swelling pressure, the swelling percentage, and the free swelling of the soils were calculated according to ASTM [20] and Holtz and Gibbs [21].

Liu et al. [22] studied the thermo–hydro–mechanical properties of bentonite–sand–graphite–polypropylene fiber (PPF) mixtures, using a sodium bentonite known as GMZ01 produced in Gao Miaozi, Inner Mongolia. They used Lianyungang quartz sand from Jiangsu, China, which is a natural quartz sea sand with SiO_2 > 96%. The experimental program involved the preparation of mixtures with varying compositions of bentonite, sand, graphite, and PPF. They determined the swelling pressure of these mixtures using a consolidometer according to ASTM D4546-08 [16]. The swelling pressure was determined as the vertical pressure needed to keep specimen volume unchanged under transverse restraint and axial loading.

Zeng et al. [23] examined the swelling pressure and hydraulic conductivity of bentonite-claystone mixtures with varying bentonite fractions and dry densities by infiltration tests under constant volume conditions. The study used MX80 bentonite from Wyoming, USA, and COx claystone from approximately 490 m depth at the Underground Research Laboratory (URL) in Bure, France. Bentonite and claystone were first crushed to a maximum grain size of 2.0 mm to achieve similar grain size distributions, contributing to a homogeneous mixture during the mixing process. The experiments were carried out with mixtures prepared in different proportions, ranging from 0 to 70% bentonite content. The swelling pressure was monitored using a force transducer, while the specimens were hydrated from the bottom with synthetic water replicating the chemical composition of the site water at the Andra URL.

Bag and Jadda [24] investigated the impact of dry density and water content on swelling pressure of monovalent and divalent bentonites, respectively, from Barmer and Bikaner, India. They used the constant-volume method using a modified oedometer to measure the swelling pressure of the soil samples. This apparatus was equipped with a load cell, positioned to directly measure the swelling force exerted by the bentonite samples during hydration with deionized water. The swelling pressures were dynamically recorded in real-time using a data logger. The swelling pressure exerted on the compacted bentonites during the hydration process was continuously recorded using a data logger that provided real-time monitoring of the swelling pressure. The design of the experiment kept the constant volume of the bentonite samples, allowing the swelling pressures to be measured under controlled conditions.

Sun et al. [25] performed tests on B75 bentonite from the northwestern Czech Republic. They focused on the effects of initial dry density, vertical load, and salinity of the pore fluid on the swelling behavior of the bentonite. Bentonite powder was compacted to specific initial dry densities and installed in a conventional oedometer apparatus. The swelling was induced by saturating the specimens either with deionized water or a 1 M NaCl solution.

3. Dataset Description

The compiled dataset encompasses 759 samples derived from experimental studies on the swelling characteristics of expansive clays. The dataset is organized into 16 distinct groups, each derived from a specific research article. This structure facilitates the easy assessment and analysis of soil data obtained from various sources. Data for each group are stored in separate tabs within a Microsoft Excel file (.xlsx format), with the tab names correspond to the descriptions in Table 1. The groups in the Excel file, as well as Table 1, are arranged chronologically based on the publication dates. Table 1 includes comprehensive details for each group in the dataset.

The dataset comprises two main categories: natural clays and bentonite with its mixtures. The natural clay category, which includes N_1 to N_5, features 463 samples ranging from disturbed and undisturbed soils collected from different regions such as Jordan, Turkey, and Saudi Arabia. These samples provide detailed information on various soil index properties such as gravel (m_g), clay (m_c), silt (m_s), and sand (m_{sa}) content, along with other key parameters such as activity (A), liquid limit (w_L), plastic limit (w_p), plasticity index (I_p), initial water content (w_i), unit weight (γ), and maximum swelling pressure (σ_{sw}^{max}).

Bentonite and bentonite mixtures represented in M_1 to M_11 include 296 samples derived from various bentonite sources such as Tsukinuno mine in Japan, Wyoming in the USA, and Gaomiaozi in China, among others. This category includes values of montmorillonite content (Mt.c), liquid limit (w_L), plastic limit (w_p), plasticity index (I_p), initial water content (w_i), dry density (ρ_d), and the corresponding maximum swelling pressure (σ_{sw}^{max}) are provided within the dataset. It should be noted that in both categories depending on the experimental study, other parameter values such as cation exchange capacity (CEC) and specific gravity (G_s) are also provided. This category includes values of montmorillonite content (Mt.c), liquid limit (w_L), plastic limit (w_p), plasticity index (I_p), initial water content (w_i), dry density (ρ_d), and the corresponding maximum swelling pressure (σ_{sw}^{max}), provided within the dataset. It should be noted that in both categories, depending on the experimental study, other parameter values such as cation exchange capacity (CEC) and specific gravity (G_s) are also provided. Violin plots in Figures 1 and 2 provide a statistical distribution of the maximum swelling pressure and other relevant properties of both natural clay and bentonite.

Table 1. Description of groups of the dataset.

Dataset	Soil Type	Swell Test Method	Study Area	Reference
N_1	Clay soils	zero swelling, swell consolidation, restrained swell, double oedometer	Jordan	Basma et al. [4]
N_2	Disturbed clay	free-swelling method	Turkey	Çimen et al. [15]
N_3	Ankara clay	free-swelling method	Turkey	Ergüler [6]
N_4	Remoulded clayey soil	swell-consolidation method	India	Rao et al. [9]
N_5	Clayey soil	constant volume oedometer	Saudi Arabia	Hakami and Seif [19]
M_1	Sodium bentonite	constant volume oedometer	Japan	Komine and Ogata [5]
M_2	FEBEX bentonite	constant volume oedometer	Spain	Villar and Lloret [11]
M_3	Various bentonites	constant volume oedometer	Japan and USA	Komine et al. [12]
M_4	Divalent rich natural bentonite	UPC-isochoric cell	Germany	Schanz and Tripathy [13]
M_5	Bavarian bentonite	constant volume oedometer	Germany	Baille et al. [14]
M_6	GMZ bentonite and sand mixture	consolidometer	China	Cui et al. [17]
M_7	Gaomiaozi bentonite	UPC-isochoric cell	China	Schanz and Al-Badran [18]
M_8	GMZ bentonite, sand, PPF and graphite mixture	consolidometer	China	Liu et al. [22]
M_9	MX-80 bentonite and COx mixture	constant volume oedometer	USA	Zeng et al. [23]
M_10	Divalent and Monovalent bentonite	constant volume oedometer	India	Bag and Jadda [24]
M_11	B75 bentonite	constant volume oedometer	Czech Republic	Sun et al. [25]

The dataset incorporates a variety of swelling test methods, each designed to assess specific soil properties under moisture change conditions. N_1 employs a combination of zero swelling, swell-consolidation, restrained swell, and double-oedometer tests to examine the swelling characteristics of compacted clay soils from Jordan. N_2 and N_3 utilized the free swelling method, offering insights into the unconfined expansion of Ankara clay and disturbed clay samples from Turkey. The swell-consolidation method, featured in N_4, provides a detailed analysis of remolded clayey soils from India.

The constant volume oedometer was used across M_1, M_2, M_3, M_5, N_5, M_9, M_10, and M_11. This method was used to examine the swelling pressure of various commercial bentonites, including sodium bentonite from Japan, FEBEX bentonite from Spain, and B75 bentonite from the Czech Republic. M_4 and M_7 used the UPC isochoric cell method for divalent rich natural bentonite and Gaomiaozi bentonite, respectively. The isochoric oedometer method in M_5 was used to analyze the swelling behavior of Bavarian bentonite, while M_6 and M_8 used a consolidometer for GMZ bentonite mixed with sand and GMZ bentonite mixed with sand, PPF, and graphite from China, respectively. Figure 3 shows the distribution of the maximum swelling pressure of bentonite and clay for each group within the dataset, respectively.

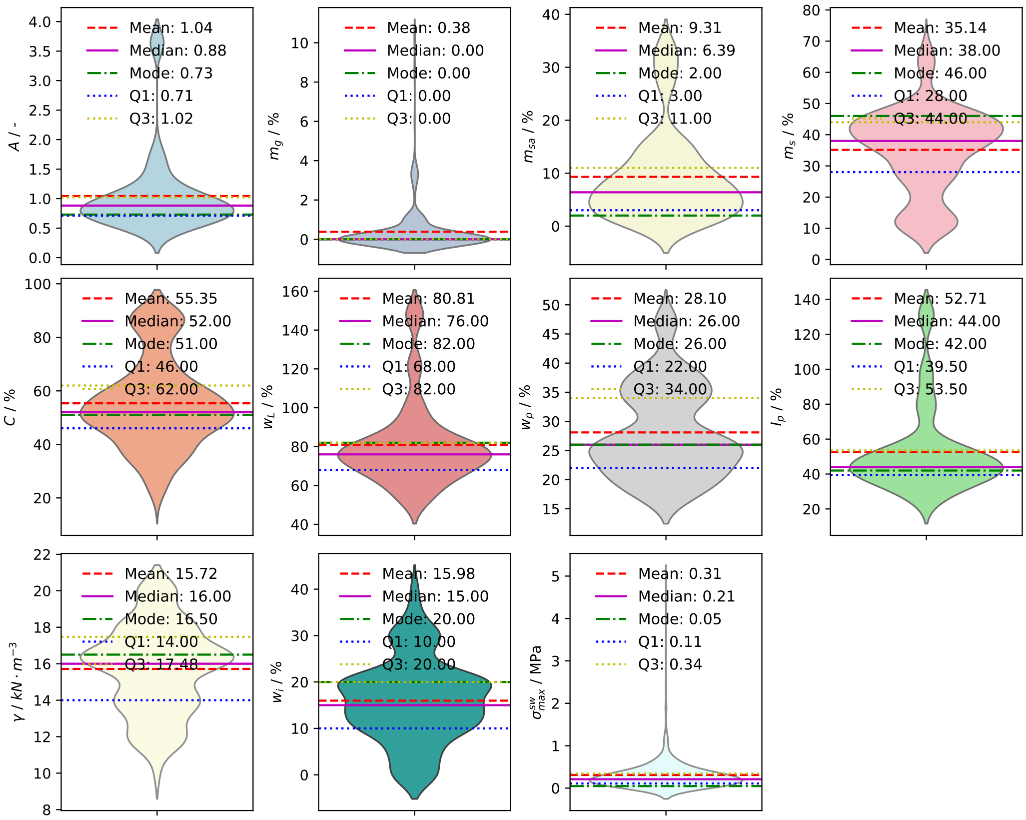


Figure 1. Statistical distribution of maximum swelling pressure of natural clay and other relevant properties.

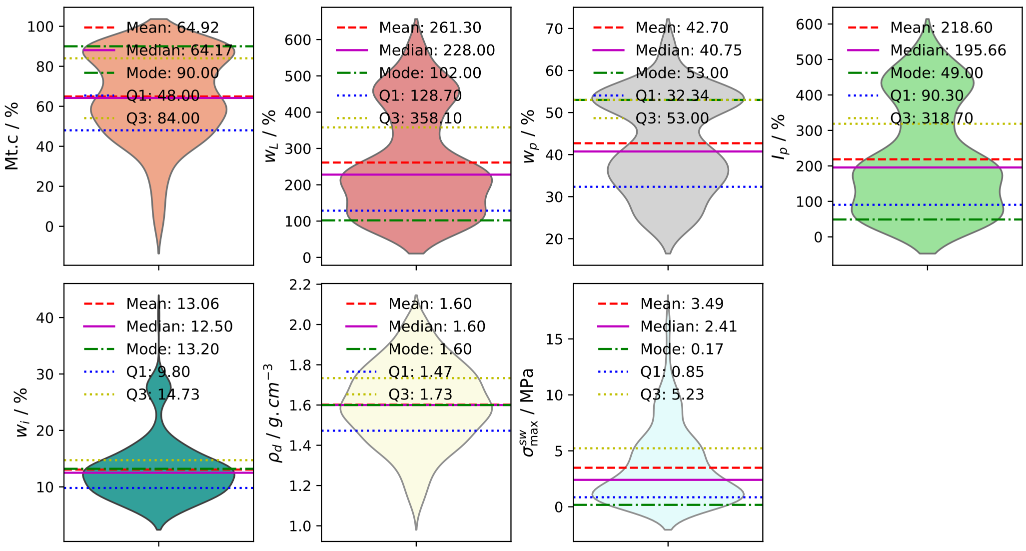
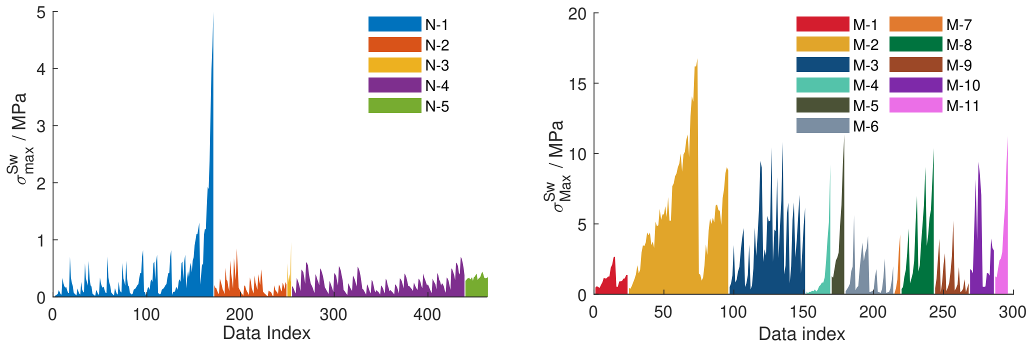


Figure 2. Statistical distribution of maximum swelling pressure of bentonite and other relevant properties.



(**a**) (**b**)

Figure 3. Distribution of maximum swelling pressure of (**a**) natural clay and (**b**) bentonite for each group within the dataset.

4. Practical Applications

The dataset presented is of significant value for a wide range of geotechnical applications, such as foundation design, slope stability analysis, landfill, containment design, and nuclear waste repositories. Engineers and practitioners dealing with expansive soils can derive practical insights from the maximum swelling pressure data to address challenges in these areas [26]. For foundation engineering, the dataset could help estimate the potential uplift pressures of structures built on expansive soils, guiding the selection of appropriate foundation types and materials to mitigate the effects of soil swelling [3]. It allows for informed decisions on using flexible materials or void forms beneath foundations in high-swelling potential areas. The dataset could also aid in evaluating the potential threats to slope stability triggered by expansive soils, particularly in response to heavy rainfall or fluctuations in groundwater levels [27]. It could also support the design of effective drainage and reinforcement solutions, such as horizontal drains, soil nails, and geosynthetics, to improve slope stability in regions with expansive soil.

In addition, in landfill and containment design, understanding the swelling characteristics of soils is essential for preventing structural failures and environmental contamination [28]. Swelling characteristics are particularly important in the design of barriers for nuclear waste repositories, where the integrity of containment systems must be guaranteed over long periods [29]. Beyond these specific applications, the dataset offers a foundation for developing empirical relationships to estimate maximum swelling pressure, developing machine learning models, and serving as inputs in numerical modeling efforts. These models and relationships can advance our ability to predict and mitigate the impacts of soil swelling in geotechnical design and analysis. This shows the broad applicability of the dataset in addressing the challenges posed by expansive soils in a variety of engineering contexts.

5. Dataset Limitations

It is imperative to recognize the limitations of the dataset for informed use. The compilation of data involved studies that utilized a variety of methods and devices to measure swelling pressure, potentially introducing variability in measurement conditions and results. Although efforts were made to ensure consistency and reliability, differences in experimental setups, soil sample preparation, and measurement techniques across the included studies could affect the comparability of data points. The dataset primarily focuses on maximum swelling pressure and does not encompass other significant aspects of soil behavior under varying environmental conditions, such as cyclic wetting and drying, temperature effects, or chemical interactions with the surrounding environment. Additionally, while the geographic representation of soil samples is broad, it does not encompass all types of expansive soils worldwide, potentially limiting the generalizability of the data to regions not represented. Lastly, employing this dataset in empirical models, machine learning algorithms, or numerical simulations requires careful consideration of its scope and underlying assumptions.

6. Methods

A systematic literature review was conducted to gather experimental data for clay soil behavior. The experimental data reported here were obtained from studies that used a variety of methods and devices to measure clay swelling pressures and other relevant soil properties. In particular, self-designed constant volume expansion devices were commonly used to measure the swelling pressure of bentonite and bentonite mixtures.

Soil swelling pressure values were reported in both tabular and graphical formats, while the corresponding soil properties were presented in textual, tabular, and graphical forms. To digitize the data, we employed a two-step process. First, we captured data by taking screenshots from graphs or tables. Then, we utilized Plotdigitizer [30] for manual data extraction from graphs and employed Excel's "data from picture" feature to directly import data from tables. Subsequently, a thorough data quality check was conducted to rectify any errors that may have occurred during the digitization process.

Relevant data on soil parameters not provided in the original data can be derived from the given parameters. The plasticity index (I_P), liquid limit (w_L), and plastic limit (w_P) are related as follows:

$$I_\mathrm{P} = w_\mathrm{L} - w_\mathrm{P} \tag{1}$$

The soil Activity index (A) can be calculated as follows [31]:

$$\mathrm{A} = \frac{I_\mathrm{P}}{2\mathrm{CF}} \tag{2}$$

where CF is the clay size fraction.

7. User Notes

The dataset is compiled from diverse sources and includes information extracted from texts, tables, and graphs, making it valuable for research and practical applications related to expansive clays. The dataset is licensed under the Creative Commons CC BY 4.0 International License, ensuring public accessibility. Furthermore, it adheres to the FAIR guiding principles for data management, facilitating its findability, accessibility, interoperability, and reusability by humans and machines [32]. We provide the dataset in a single Microsoft Excel file, designed to be user-friendly for researchers and inexperienced end-users.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

Symbol	Description
A	Activity index (-)
ATT	Axis-translation technique
ASTM	American Society for Testing and Materials
CEC	Cation exchange capacity ($meq\,g^{-1}$)
COx	Callovo–Oxfordian
e	Void ratio (-)
G_s	Specific gravity (-)
I_p	Plasticity index (%)
C	Clay content (%)
m_g	Gravel content (%)
m_s	Silt content (%)
m_{sa}	Sand content (%)
γ	Unit weight ($kN\,m^{-3}$)
σ_{sw}^{max}	Maximum swelling pressure (MPa)
Mt.c	Montmorillonite content (%)
VET	Vapor equilibrium technique
w_i	Initial water content (%)
w_L	Liquid limit (%)
w_p	Plastic limit (%)
PPF	Polypropylene fiber

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