Research Article

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Experimental and numerical evaluation of tire rubber powder effectiveness for reducing seepage rate in earth dams

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Abstract: Tires waste is an undesirable urban industry surplus that has grown worldwide yearly. Because of its seals, this material may be used in earth dams, one option for disposing of this waste. Since this is the main objective of this study, an experiment on a soil sample with various ratios of rubber powder has been conducted to better comprehend the impact of tire rubber powder (TRP) on the seepage rate in earthen dams. This study used physical and numerical models to investigate seepage through earth dams. Analysis indicates that the plotted seepage line in SEEP/W software was comparable to the observed seepage line in the physical model. TRP was tested at concentrations of 15, 30, and 50%. The research demonstrates that there has been a noticeable improvement in reducing the seepage rate through the dam's body; seepage was decreased by 11.28% when a 15% ratio was adopted, a far smaller impact than the other percentages. The proportion was consequently raised to 30%. The seepage rate was found to be reduced by 35.6%, and TRP with a 50% ratio showed excellent behavior in lowering the water level (phreatic line) from the core point to the downstream face *D*/*S* and reducing the seepage rate by 41.5%, producing significantly better results. The findings in SEEP/W software indicate that the relative error in seepage rate varies, averaging 11.8% for the first model, 12.18% for the second, 1.65% for the third, and 7.63% for the fourth. The first and second physical models' seepage rate (relative inaccuracy) dramatically increased as a result of the presence of piping.

Keywords: tire rubber powder, earth dams, phreatic line, seepage, sustainable development, SEEP/W software

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1 Introduction

1.1 Research background

The development of any country's economic growth depends significantly on water resource initiatives, particularly dam construction. The most significant hydraulic structure that has been created on a river is undoubtedly a dam. Dams have been essential for controlling flooding [1]. In Iraq, the majority of dams serve several purposes. Since significant financial returns and extravagant sums are lavished upon their foundations, dams are among the most critical significant foundations in the nation. If these dams fail to fulfill their intended functions or malfunction, serious consequences could follow. Throughout their initial construction and operation, numerous dams have collapsed worldwide.

The three main types of earth dams are homogeneous, zonal, and diaphragm earth dams [2]. The most common and affordable type of dam is an earthen dam. It frequently has a wide foundation and a trapezoidal shape. In an earth dam, a non-overflow with a different spillway is constructed. Seepage is one of the leading causes of earth dam failure. Use an impervious zone or core in an earth dam to control seepage and prevent the earth dam's structure from deteriorating, which could lead to a sudden failure from piping or sloughing [3–5]. Consequently, the focus should be on enhancing the physical properties of soil, reducing dam seepage, and optimizing dam construction with sustainable engineering.

Sustainable engineering focuses on the future impact of what is currently being designed and operated and how these designs can be made suitable in the long term and more beneficial with the least harm to the environment and limited resources. This contrasts with short-term design and implementation that seek to achieve direct benefit without considering future ramifications. The fundamental objective of sustainable engineering is to increase growth and prosperity in the present and future while considering the effects of resource use on the environment, the people, and the stock of resources that will be accessible. Where possible, the environment must be protected, and it must be made a priority to produce things that will help, not hinder, the development of future projects [6–9].

Understanding the significant hazards associated with engineering that does not consider the long term gives rise to the need for sustainable engineering. Damaged car tires are an environmental burden on the nations that use them because they take hundreds of years to decompose and create a hazardous environment when burned to get rid of them. This is because burning damaged car tires releases toxic gases like lead, carbon, and sulfur oxides (Figure 1). Globally, geotechnical engineers are looking for innovative substitute materials that can be used for both cost-effective ground improvement methods and the preservation of finite natural resources. The two global phenomena of the twentieth century have been industrialization and urbanization; the main adverse effects of industrial wastes (incinerator ash, plastic trash, rice husk ash, used tires, etc.); and the issues with managing and safely disposing of them. Increasing waste production in the modern world has resulted in a number of environmental issues. As a result, many academics and researchers attempt to resolve this issue by recycling these substances differently [10,11]. Therefore, one of the industry's most significant issues is the safe and efficient disposal of these wastes [12].

Rubber aggregate (rubber powder) is one of the many valuable products for recycling which utilized in engineering projects and public works, including backfilling retaining walls, leveling slopes, repairing roads, and isolating underground highways, besides that investigation into recycled rubber's potential as a light-weight backfill material [13] and most important to minimize the amount of seepage in the dam body, earth dams might utilize this material because of its seals, and this is the main focus of our experiments.

Waste products, including used tires, ash, and wastewater sludge, present an environmentally, economically, and fundamentally proficient alternative. Once the rubber percentage in the mixture approaches 30%, the soil tire powder's strength drops because the mixture's behavior resembles that of a fuse chip mass with sand rather than reinforced soil [14]. As a result, mixing waste tires, ash, and wastewater sludge also showed good potential for soil stabilization [15–17].

Numerous research studies have investigated the advantages of using tires rubber powder to enhance various soil properties, such as reducing the permeability and compressibility of the soil mass. However, since applying tire rubber powder (TRP) for this purpose, verification of its effectiveness has not been performed. Thus, it is necessary to evaluate this material's ability to be reused in earthen dams. This

Figure 1: Burning rubber tires is one of the sources of pollution with toxic elements and compounds.

study aims to determine whether using tires rubber powder in different ratios may effectively reduce seepage in earth dams.

1.2 Study of seepage through earth dams

The study of a more scientific methodology for planning and constructing dams was motivated by the dam failures identified in the 1700s and 1800s. Henri Darcy published the first research that statistically depicted fluid flow through a porous medium in 1856. Darcy based his formula, commonly known as Darcy's law, on the flow of water across vertical filters in laboratory setups [18]. Through various experiments, he was able to demonstrate a straightforward correlation between the hydraulic gradient and discharge velocity, which he described as follows:

$$\vartheta_\mathrm{d} = k\cdot i = Q/A, \tag{1}$$

$$Q = k\cdot i\cdot A, \tag{2}$$

where ϑ_d is the discharge velocity (LT^{-1}), k is the hydraluic conductivity (LT^{-1}), A is cross sectional area normal to the direction of flow (L^2), Q is the discharge rate (L^3T^{-1}), and is the hydraluic gradient (L/L).

1.3 The uses of physical and numerical models

Numerous studies have been carried out using physical models, despite the fact that the analysis of hydrological and geological conditions in locations is required for the study of seepage through earthen dams (e.g., [19–21]) because physical models can describe the phreatic line and the flow rate, as well as the overall seepage behavior through earthen dams. In addition, testing performed on physical models may be a crucial tool for analyzing seepage behavior before the building of earth dams and assisting in validating the basic design of dams by identifying any deficiencies in a proposed design.

However, as to the numerous limitations and restrictions associated with physical modeling, numerical modeling, which is based on mathematical solutions, is progressively being employed in research (e.g., [22,23]) to solve the most challenging engineering issues, which include seepage. Numerical modeling is a quick and affordable technique, and the findings may be easily shared with the parties involved. Numerical modeling is fundamentally different from laboratory-scale physical and full-scale field modeling since it is a purely mathematical method [24].

Physical modeling is typically advised when numerical modeling is seen as inadequately verified, such as when complicated hydraulic circumstances, unusual or atypical site characteristics, or project performance is expected to improve.

In this study, seepage through earth dams was investigated using physical and numerical methods, and the findings were then compared with the use of the SEEP/W program.

1.4 Numerical modeling using SEEP/W software

A numerical model that uses the finite element approach is the SEEP/W software. It can mathematically simulate the physical behavior of water that flows through a particulate material. The program discusses the fundamental flow laws for transient and steady-state flow and demonstrates how these laws are represented numerically. Darcy's law, the partial differential flow of water equations, the finite element flow of water equations, temporal integration, integrals, the permeability matrix, the mass matrix, flux boundary vectors, and density-dependent flow are the mathematical formulas utilized in SEEP/W. In this research, the SEEP/W software was used to trace the phreatic line across the four physical models of earth dams and determine the seepage amount through the models. In SEEP/W, the following mathematical equations are included:

1. Darcy's law: The experiment showed a direct relationship between hydraulic gradient and discharge velocity:

$$V = k\cdot i = Q/A, \tag{3}$$

where v is the Darcian velocity, k is the coefficient of permeability, and i is the hydraulic gradient.

2. Partial differential water flow equations: The fundamental governing differential equation for two-dimensional seepage may be expressed as follows:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right) + Q = 0. \tag{4}$$

The conductivity in the x-direction is equal to the conductivity in the y-direction once the condition is isotropic and homogenous, and the equation transforms to

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0. \tag{5}$$

3. Finite element water flow equations: The following is the finite element method equation for a study-state circumstance where there is no time-dependent function:

$$\tau\int([B]^T[C][B])\mathrm{d}A\{H\}, \quad (6)$$

which is equal to the flow $[Q]$, where $[B]$ is the gradient matrix, $[C]$ is the element of the hydraulic conductivity matrix, $\{H\}$ is the vector of nodal heads, and τ is the thickness of an element.

The simplified form of the finite element seepage equation is as follows:

$$[K]\{H\} = \{Q\}, \quad (7)$$

where $[K]$ is the characteristic matrix element and $\{Q\}$ is the applied flux vector element.

4. Numerical integration and mass matrix: Gaussian numerical integration is used by SEEP/W to assess the mass matrix and the element characteristic matrix. The element properties are sampled at certain locations, and the integrals are generated by averaging those samples throughout the whole element.

$$[K] = \tau\int([B]^T[C][B])\mathrm{d}A. \quad (8)$$

Hence the following is the description of the element mass (or storage) matrix:

$$[M] = \tau\int(\lambda < N >^{\mathrm{T}} < N>)\mathrm{d}A, \quad (9)$$

where λ is a storage duration and equal to $(m_{\mathrm{w}}\gamma_{\mathrm{w}})$ for a transient seepage and m_{w} is the storage curve's slope.

1. Hydraulic conductivity matrix: The basic formula of the numerical model element's hydraulic conductivity matrix is as follows:

$$[c] = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}, \quad (10)$$

where

$$c_{11} = k_x\cos^2\alpha + k_y\sin^2\alpha, \quad (11)$$

$$c_{12} = k_x\sin\alpha\cos\alpha + k_y\sin^2\alpha, \quad (12)$$

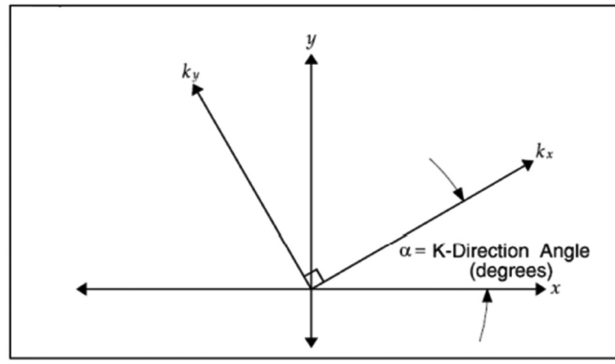

Figure 2: Hydraulic conductivity matrix parameters definition.

$$c_{12} = c_{21}, \quad (13)$$

$$c_{22} = k_x\sin^2\alpha + k_y\cos^2\alpha. \quad (14)$$

The parameters k_x, k_y, and α are defined as in Figure 2.

2 Materials and experimental methodology

A laboratory channel model setup was constructed in the Wasit University's Faculty of Engineering labs. It consists of several primary and auxiliary parts that collaborate to carry out the device's intended purpose while upholding the principles of physical modeling. The significant parts of the apparatus consist of a 6-m steel frame, a sealed tank, a slate raft to control the level of water, and Plexiglas windows (1.1 by 1 m) with dimensions of 1 m in depth and 0.8 m in width.

A laboratory model was made with dimensions of 6 m in length and 0.8 m in both height and width, see Figures 3 and 4 of the dam model at slopes of 2.5:1 at U/S and 2:1 at *D/S*. The model has been built on ratios and equations within the relationship between both the dimensions of

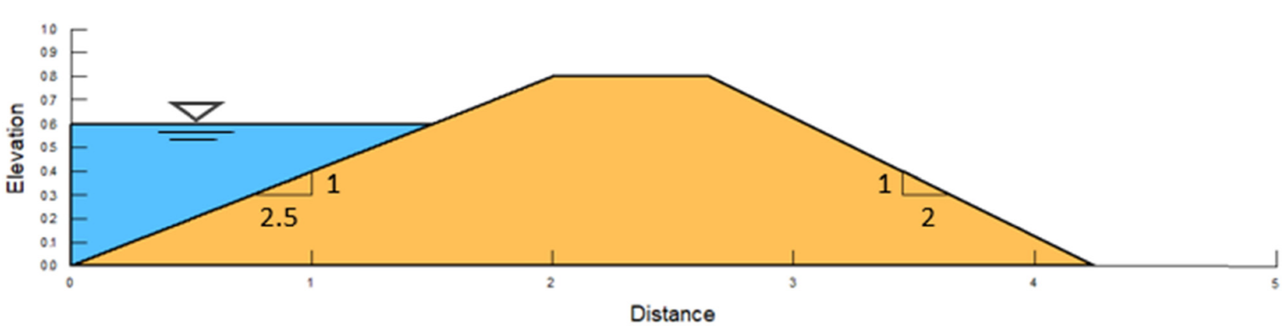

Figure 3: Homogenous dam type without rubber powder (TRP).

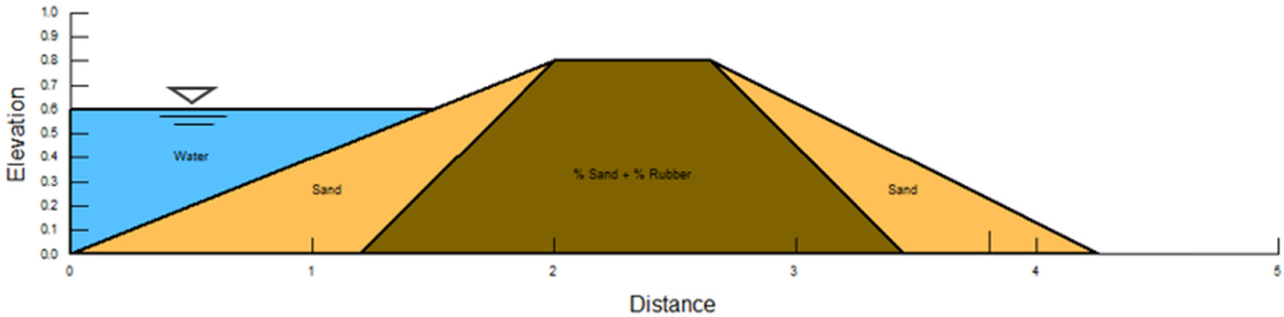

Figure 4: Zoned dam type with rubber powder (TRP) core at slope 1:1.

the dam and the stress applied to it, thus it is a physical model, not a miniature model of the dam or a simulation of the existing dam in accordance with Terzaghi and Strange's recommendations, every requirement has been adjusted [25,26]. The physical model's construction requires compaction. To fit the drainage's thickness, the first layer has been laid out at a thickness of 10 cm. To ensure that the compaction is effective, the subsequent layers have been added at intervals of 15 cm.

Besides ten sensors being used to investigate the water level inside the body of the dam, the pressure sensor, depicted in Figure 5, is a sensor made specifically for this purpose by WNK Co., China, out of stainless steel with ceramic material. It detects the water pressure to determine the hydraulic head on an earthen embankment. It has properties that prevent corrosion.

The specifications of these sensors are as follows: model number WNK811, precision (0.5–1)%, thread size G1/4, wire length 2 m, power supply voltage 5 V, and the measurement range is 10 kPa. Each pressure sensor was connected to the Lab Jack T7-PRO data logger, which transfers electronic signals to the computer. The sensors' locations are illustrated in the schematic diagram shown in Figure 6.

The state-owned company for the rubber and tire industries in Al-Diwaniyah, Iraq, provided tire powder with a diameter of less than 1 mm. In a homogenous dam model, TRP was mixed with the model's sand soil, see Figure 7. Three different proportions of TRP (15, 30, and 50%) has been used to observe how this powder affected the seepage rate through earth dam. When the reservoir was fully topped off, the experiments were run in a risky scenario (0.6 m), see physical models in Figures 8 and 9.

2.1 Grain size distribution test

A sieve analysis test was used to identify the particle's grain size distribution. The test was carried out in accordance with the Iraqi specification (no. 45/1984), it was carried out using a vibrator-type sieve shaker (ASTM C136). Figure 10 displays each sample's distribution curve for soil with and without TRP.

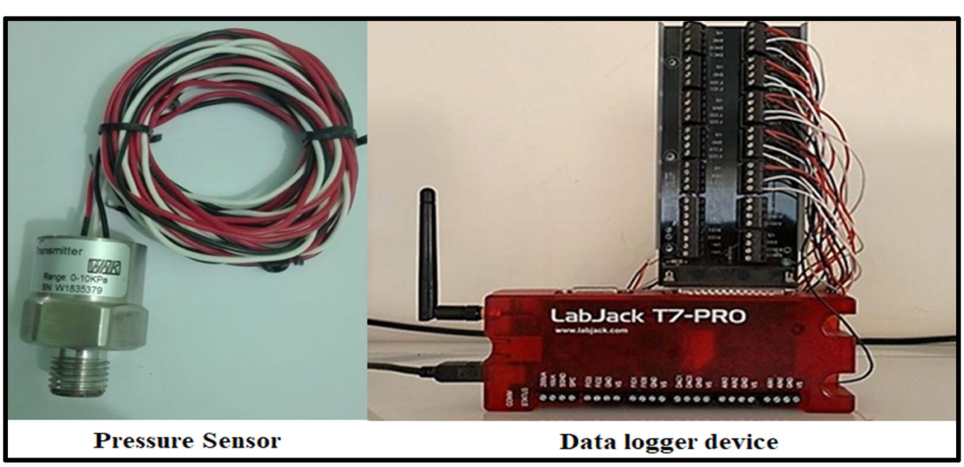

Figure 5: The pressure sensor and data logger device.

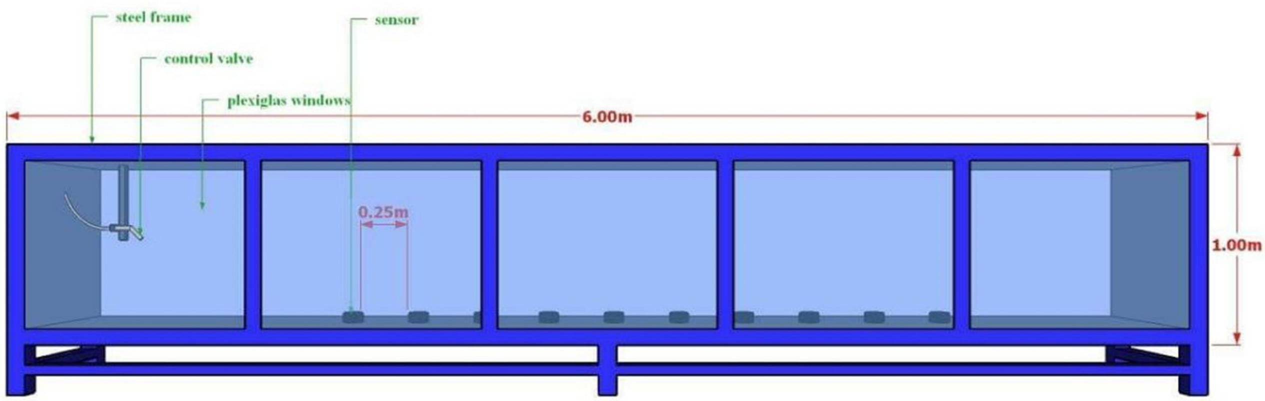

Figure 6: A schematic diagram of the principal components.

Figure 7: Tire powder used in the experiments.

Figure 8: Physical homogenous dam model without TRP core.

2.2 Hydraulic conductivity (*K*)

The coefficient of permeability for two types of soil before and after adding TRP was determined in this experiment using the constant head method, and the findings were verified in a laboratory to determine the samples' *K* value in accordance with ASTM D 2434. 3.41×10^{-4}, 3.29×10^{-4}, 2.11×10^{-4}, and 1.55×10^{-4} for soil without TRP, 15, 30, and 50% TRP, respectively, and these values are used in SEEP/W software. Hydraulic conductivity may be calculated using Darcy's equation:

Figure 9: Enhanced homgenous dam model with TRP core at slope 1:1.

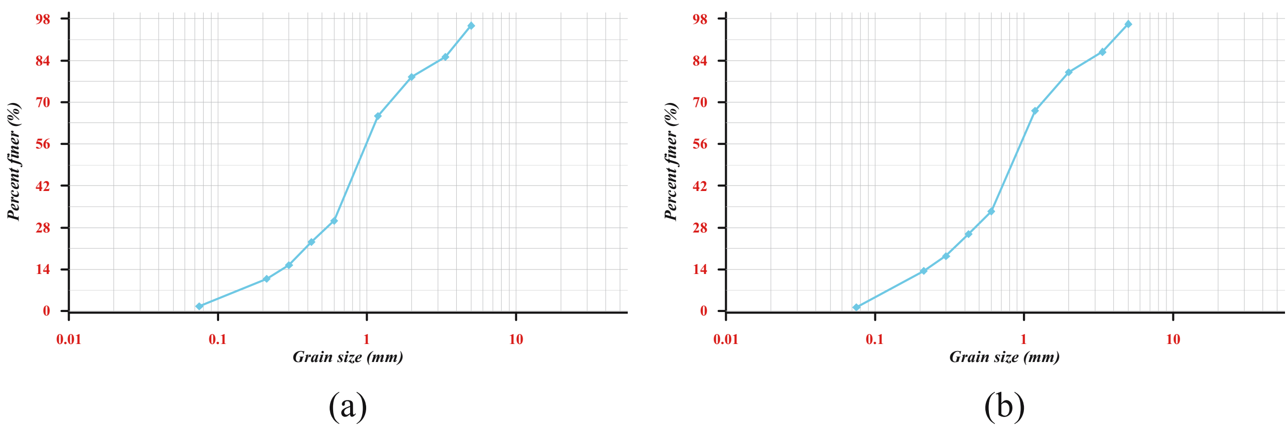

Figure 10: Particle size distribution for dam soil: (a) without TRP and (b) with TRP.

$$K = \frac{QL}{hA}, \tag{15}$$

where Q denotes discharge (mL/s), A is the cross-section area of the tube (cm^2), K is the hydraulic conductivity (cm/s), L is the length of the sample (cm), and h is the hydraulic head (cm).

3 Results and discussion

The tests were run on the prepared models mentioned in the preceding section. Physical model saturation lasts for 2–4 days. The phreatic line is drawn based on the water level in the sensor indicator when the dam materials reach saturation and have a steady seepage rate. Three different powder percentages have been experimented with, and it was found that the proportion of 15% had a nearly little impact on the amount of seepage through the dam's body by about 11.28% from the physical model without TRP. The proportion was consequently raised to 30%; it was observed that the seepage rate was reduced to 35.6%, while the water level indicator (phreatic line) within rearward sensors just after the core was lowered in comparison to the various proportions of TRP used, as shown in Figure 11.

The final ratio of 50% demonstrated excellent behavior in decreasing the water level behind the core point and significantly better results in reducing seepage through the body of the dam by 41.5%; the effects of seepage flow rates for the models with and without rubber powder are summarized in Table 1.

The experimental results of the physical models reveal that the phreatic line in the first model without TRP cuts downstream, which affects the dam's stability and leads to failure of the downstream slope, as shown in Figure 12. There was no failure, and the seepage line did not cut the D/S of the dam at level 0.6, which is considered to be the most significant level for the dam when TRP material by 15% was added, so it can be seen that adding rubber powder to the soil may give more stability and prevent failure but did not significantly modify the seepage rate compared to the previous model without TRP core.

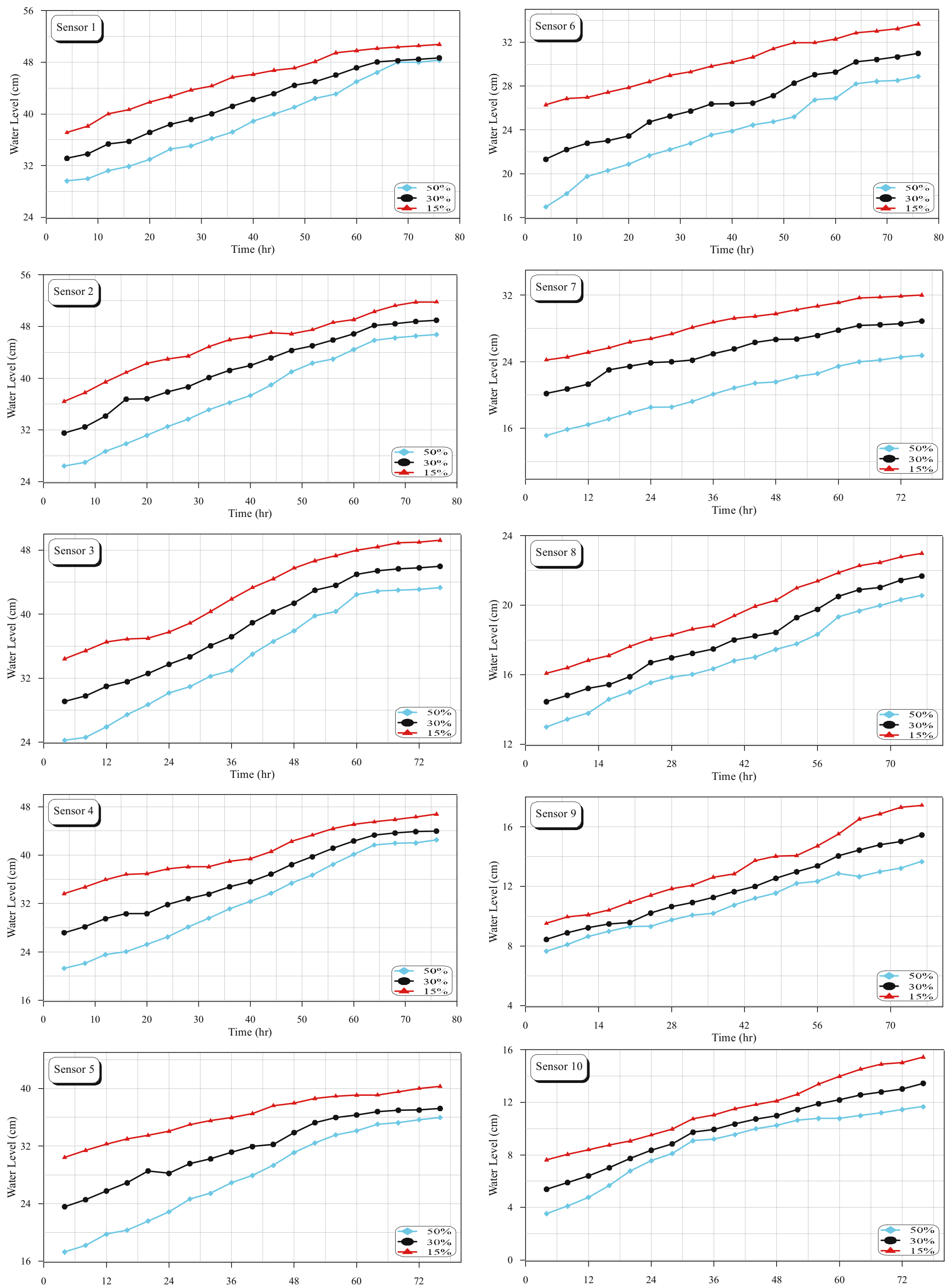

Figure 11: The water level indicator in comparison to the various proportions of TRP used.

Table 1: Seepage flow rates between SEEP/W and physical models

Models	Seepage (q) (m^3/s/m)	
	Physical	SEEP/W
Model no. 1 Homogenous without TRP core	3.91×10^{-5}	3.4449×10^{-5}
Model no. 2 with 15% TRP core	3.46×10^{-5}	3.0384×10^{-5}
Model no. 3 with 30% TRP core	2.51×10^{-5}	2.4684×10^{-5}
Model no. 4 with 50% TRP core	2.28×10^{-5}	2.1060×10^{-5}

Figure 12: Failure in the *D*/*S* slope of the first model due to seepage line.

On the other hand, models with 30 and 50% exhibited a massive reduction in seepage rate. Moreover, the model with 50% TRP shows excellent behavior in reducing the water level beneath the core point. Therefore, it can be demonstrated that the presence of the TRP core significantly reduces the seepage rate and maintains the phreatic line within the dam body, as illustrated in Figure 13.

Results from the SEEP/W are illustrated in Figure 14. The findings indicate that the first model's phreatic line cut the *D*/*S* at elevation 31.7702 cm, while the physical model cuts the *D*/*S* at elevation 30.0394 cm, which can be attributed to laboratory conditions and other soil properties, including compaction and water saturation of the soil, which are not sufficiently covered in SEEP/W; this ends up causing soil sloughing and earth to fall off banks and slopes because of a loss in cohesion [27]. Very wet soil is one of the leading causes of soil sloughing off, which occurs for the same reasons as landslides generally do [28]. Sloughing affects the uppermost soil layers; however, this may end in massive slope failure.

It is noted that the phreatic line findings for the physical models and SEEP/W are relatively similar. Despite this, the relative error in the seepage rate fluctuates, averaging 21.89% for the first model, 12.2% for the second, 1.17% for the third, and 7.5% for the fourth. Due to the existence of piping, the first and two physical models' seepage rate (relative error) significantly increased. The relation between pore water pressure and distance for each model is illustrated in Figure 15 using the SEEP/W graph. This occurs because seepage flow intersects the *D*/*S* slope, causing water to exit the dam body as surface water, and because piping may begin to develop inside the body of the physical dam model, and the second reason for this relative error is probably a result of the soil not being sufficiently compacted.

The sensor readings and piezometric readings of the phreatic line between SEEP/W software and physical models are depicted in Figure 16 using the SPSS program. This comparison's correlation value of over 95% shows that the SEEP/W program produces reliable findings.

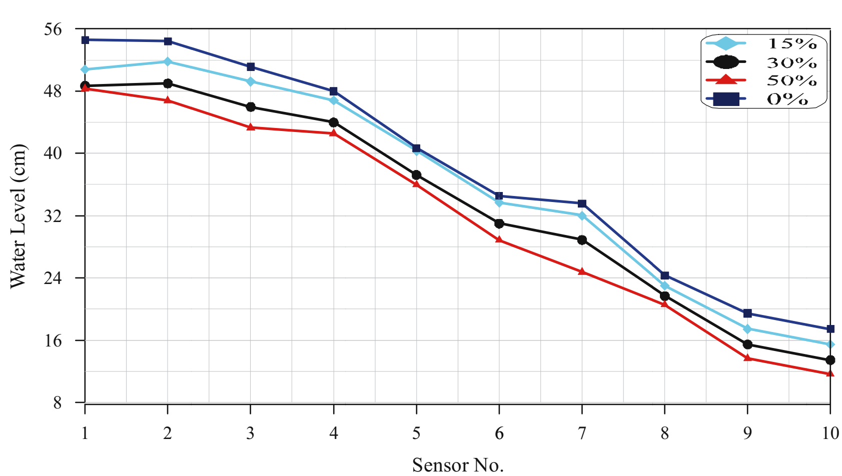

Figure 13: Phreatic line of the physical model at steady state condition.

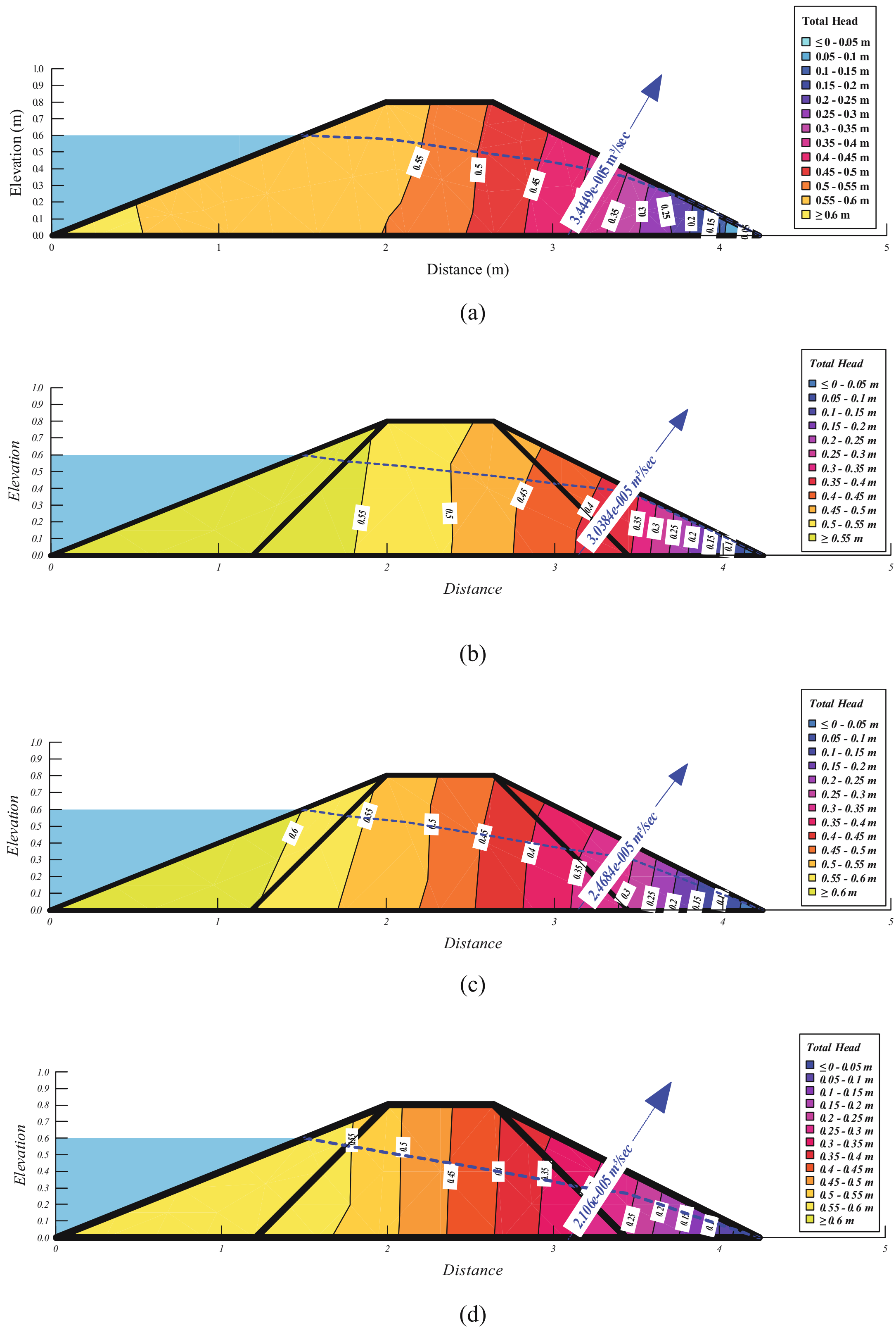

Figure 14: Seepage line, flux section at *D/S*, and the contours of the total head for the four models using the SEEP/W software. (a) Model no. 1, (b) Model no. 2, (c) Model no. 3, and (d) Model no. 4.

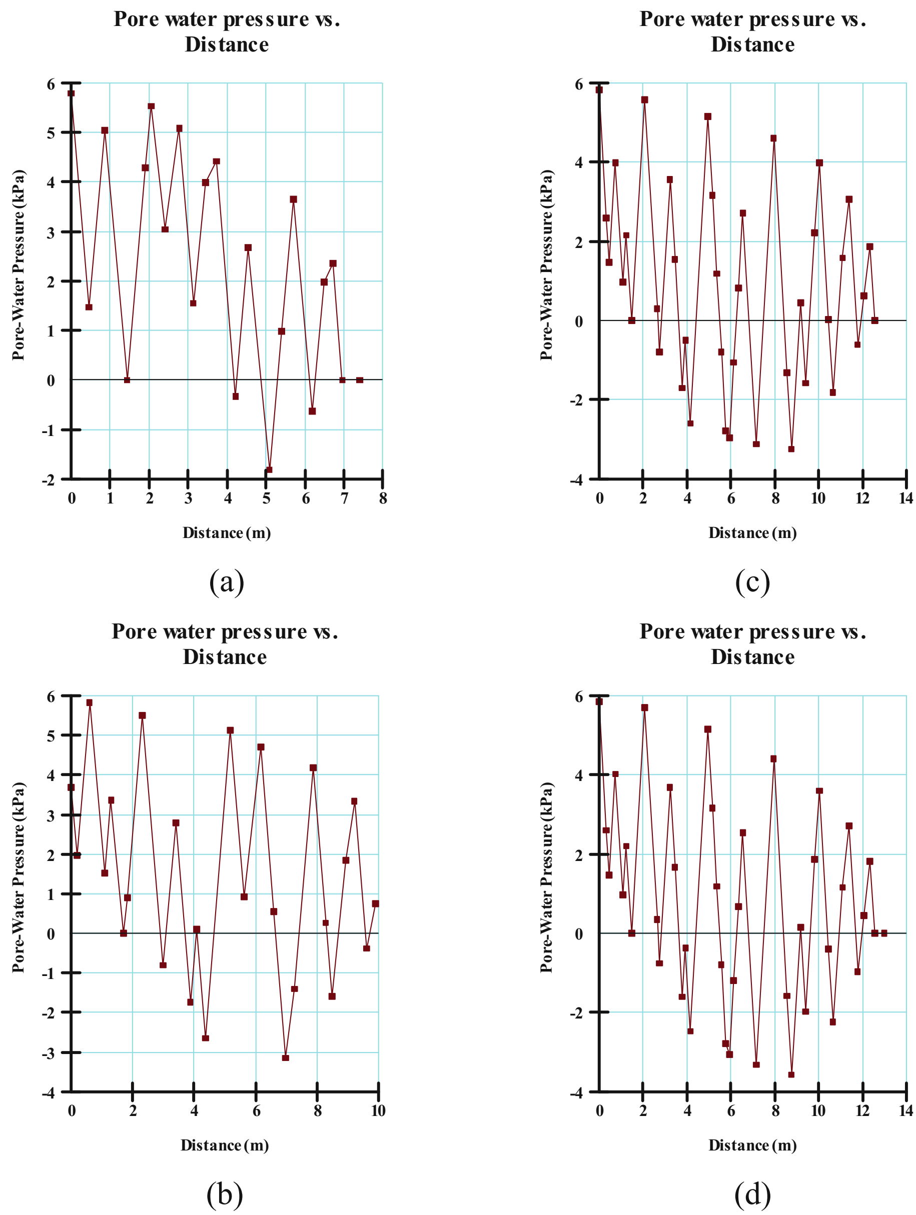

Figure 15: Relation between pore water pressure and distance for four models. (a) without TRP core, (b) with 15%, (c) with 30%, and (d) with 50%.

4 Conclusions

TRP was used in homogenous earthen dams to reduce the seepage rate. Four models were adopted with three proportions of TRP: 15, 30, and 50%. Based on the test findings of this study, the following conclusions were drawn:

1. Due to the massive seepage flow rate and failure developing at the maximum level (0.6 m), more ever, excessive seepage line, the model without tires rubber powder core is not recommended.
2. According to the experiments, adding 15% rubber powder to the soil has almost a little effect on reducing seepage amount. However, if TRP's core exists, the phreatic line always remains within the dam body.
3. The model with 30% of rubber powder is recommended over that with 50% based on economic cost and quality of seepage improvement, in addition to almost a slight seepage rate reduction.
4. The findings indicate that SEEP/W software can simulate seepage through both homogeneous and non-

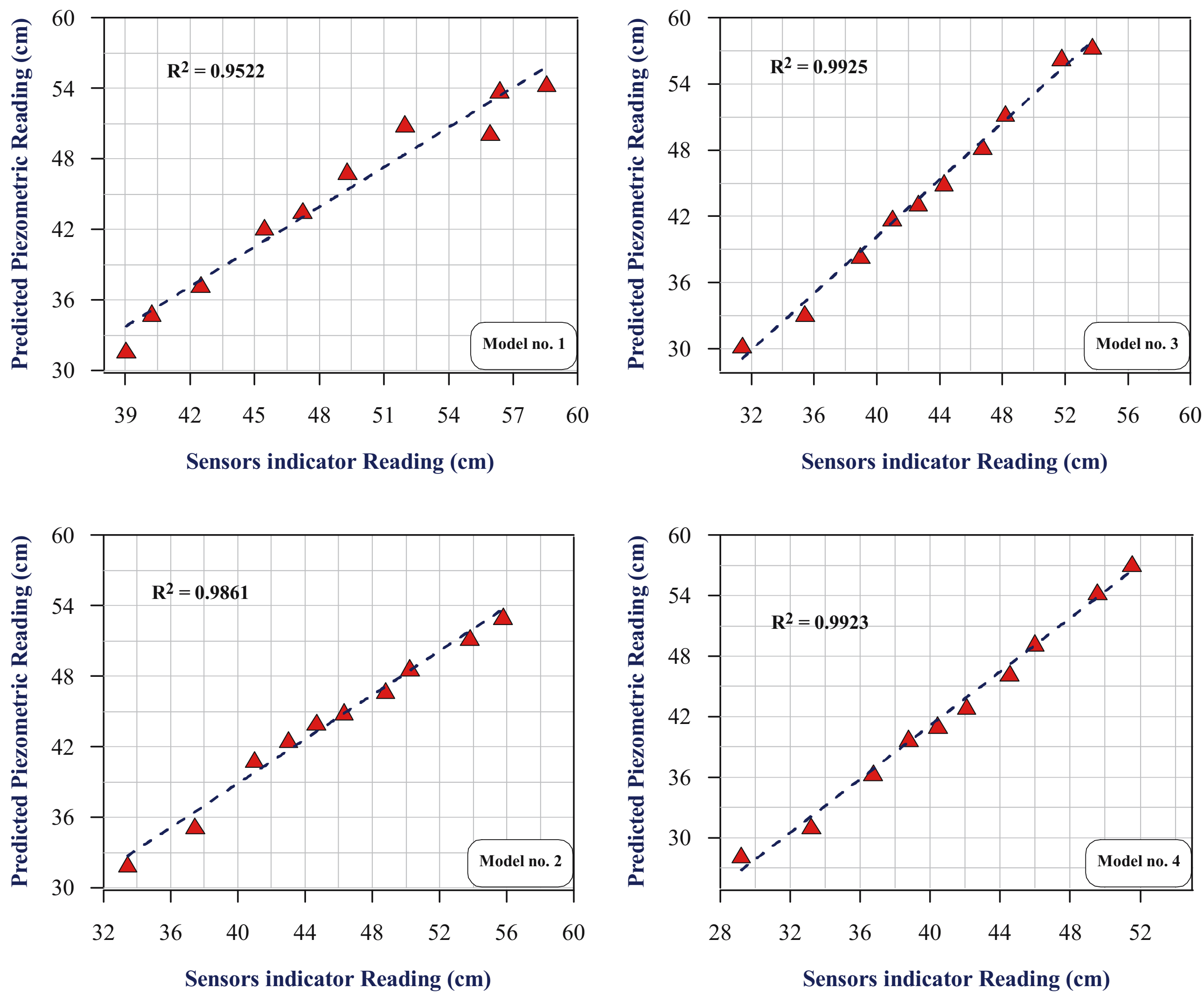

Figure 16: Sensors indicator reading and piezometric reading between physical models and SEEP/W.

homogeneous earth dams with a high level of accuracy between experimental and numerical models. This comparison's correlation value of over 95% shows that the SEEP/W program produces reliable results.

Finally, it is observed that the TRP addition had a quite significant impact on decreasing the seepage rate in addition to lowering the phreatic line in the physical models, consequently minimizing the possibility of failure when the seepage line cuts the *D*/*S* slope.

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Conflict of interest: The authors state that there is no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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