Heat and water flux modeling in an earth dam

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ABSTRACT
This study aims to identify the water flux in an earth dam using heat flux due to convection. Sixteen earth dam models were constructed in a hydraulic flume by varying geometrical and flow input parameters to identify heat and water flux. Homogeneous as well as earth dams with clay cores were built in a hydraulic flume. Temperature measurements were done to calculate heat flux in the experimental model. A finite element model of the earth dam using Seep/w was developed to obtain water flux, while Temp/w was used to obtain heat flux. These results were used as input in Temp/w and Seep/w in Geostudio 2020. Significant reduction of the heat and water flux was seen while comparing the homogeneous models with central impervious core models. An increase in the heat and water flux was observed on increasing the downstream filter’s length, longitudinal slope, and vice versa with the upstream slope and the thickness of the clay core. Comparing fluxes in a homogeneous dam model (model 1) with the clay core model (model 9) with top width 2.4 m and bottom width 18 m in model 9, both water flux and heat flux were reduced by 78.46%. While comparing it with model 10, with bottom core width of 18 m and top core width of 1.9 m, both water flux and heat flux reduced by 77.72%. Heat flux measurements were found to be a valuable alternative to detecting water flux and seepage in an earth dam at a reduced cost.

Key words: convection, earth dam, heat flux, porous medium, temperature, water flux

HIGHLIGHTS
• This study identifies the heat due to the convective heat transfer in the respective earth dam model and water flux due to seepage in a porous medium such as earth dams by varying geometrical and flow input parameters.
• A finite element model using Seep/w was used to determine the water flux, and Temp/w was used to obtain heat flux.
• It was observed that near walls of a hydraulic flume, soil pores of the earth dam were of larger volume, resulting in an increased local water flow.
• Increased heat and water fluxes were observed when the downstream filter length and longitudinal slope were increased, and vice versa with the upstream slope and thickness of the clay core.
• Heat flux obtained was a practical alternative in detecting seepage and water flux in an earth dam.

1. INTRODUCTION
Earthen dams are simple and cost-effective structures made of soil based on silicon that stand on their self-weight to prevent sliding and overturning. Earth dams are prone to seepage, and inadequate seepage may cause stability problems as it leads to a reduction in the shear strength of the dam, which could lead to its failure.

Radzicki & Bonelli (2010) applied an Impulse Response Function Thermal Analysis model to detect leakage in an earth hydraulic structure – an earth dam and dikes. Chen et al. (2009) developed a Finite element method-based model of fully coupled multiphase flow, thermal, and stress/deformation in a porous geological media. A three-dimensional software name 'THYME3D' was also developed. Johansson & Sjödahl (2004) inspected the downstream toe of about ten embankment dams to detect seepage with data obtained by measuring temperature. Yousefi et al. (2013) studied leakage in earth-fill dams using seepage flow and thermal simulation. Convective diffusion equation and mass balance were discretized using the finite element analysis in saturated and unsaturated zones. Results showed that temperature variation was more effective for inspection of leakage than the piezometric seepage levels. Alekseevich & Sergeevich (2017) developed a thermal-seepage regime numerical model based on the finite element method for dam foundations operated in permafrost conditions. Several factors that affect the temperature measurement were the thermal conductivity of soil, microclimate,
and the vegetation in the area. It was found that the amount of water rising can be estimated by computing the amount of heat energy transferred to the surface.

Abu-Hamdeh (2014) studied the effect of water content and bulk density on the specific heat and volumetric heat capacity in a laboratory on sand and loam. The calorimeter method was used to determine the specific heat of both types of soils. It was found that the specific heat increases with increasing moisture content of the soil. In contrast, the volumetric heat capacity increased with increasing the soil density and its moisture content. On similar moisture content and soil density, loamy soil had higher specific heat and volumetric heat capacity than the sandy soil. Amanifard et al. (2007) investigated the effect of an electrical double layer (EDL) near the solid/liquid interface on a three-dimensional heat transfer characteristic. Numerical investigation on the pressure drops of water flow through a rectangular microchannel was also carried out. It was observed that the liquid flow in rectangular microchannels was influenced significantly by the EDL, especially in the high electric potentials. Del Piero (2020) proposed a heat conduction theory in rigid heat conductors based on mechanical concepts and compared it with traditional thermodynamic theories. It was found that the proposed mechanical approach provided the same equation as the thermodynamic approach but in a simpler way. Badruddin et al. (2020) reviewed heat transfer in porous media in various geometrical shapes like a vertical plate, cylindrical shape, cavity, etc. Heat transfer in natural convection, mixed convection, thermal equilibrium, and thermal non-equilibrium was also explained for the review’s purpose. Cuong et al. (2017) reviewed temperature measurement to estimate seepage in an embankment dam. The downstream toe was highlighted as the most important location to detect the seepage using fiber optic sensors. Short-term temperature analysis was good for estimating localized leakage, which helps minimize the cost of repair works. It was also reviewed that from the temperature measurements, seepage velocity can be evaluated.

Buntebarth (2020) determined the thermal conductivity and the thermal diffusivity of dry granular material by heat transfer between the source and the investigation media. An empirical relation was established between the thermal conductivity and the diffusivity of the media. Misra et al. (1995) presented a review on factors affecting soil thermal conductivity. They determined soil thermal conductivity by empirical and semi-empirical methods of five soil types: gravel, sand, silt, clay, and peat. A theoretical thermal conductivity model of granular soil material was developed in an almost dry phase. Abu-Hamdeh (2003) investigated the effect of water content and bulk density on the specific heat, volumetric heat capacity, and sandy and clay soil’s thermal diffusivity. Laboratory experiments were performed using the calorimetric method. The results also observed that the clay soil generally had higher specific heat and volumetric heat capacity than sandy soil. Chuvilin & Bukhanov (2019) conducted an experimental study to determine the thermal conductivity of frozen soil at gas pressure below equilibrium using a KD-2 needle probe which caused a little impact on the soil samples in the study area.

Kurz et al. (2017) presented experimental laboratory results to estimate the thermal conductivity of frozen and unfrozen soil samples of clay, silt, and peat subjected to seasonal freezing and thawing at the study area. Thermal conductivity values obtained from empirical methods were compared with the value obtained from a thermal probe in the laboratory. Kodešová et al. (2013) measured thermal conductivity and heat capacity using a KD2 PRO device with 15 TR-1 and SH-1 sensors. The results measurement observed that the highest thermal conductivities were measured in soils on quartz and substrates.

2. SOIL PROCUREMENT AND ITS TESTING

The soil was procured from a depth of 2 m below the ground level of the ground of Delhi Technological University, Delhi, India (28.7501° N, 77.177° E). The soil’s geotechnical properties, used to construct the dam in hydraulic flume, were tested in the laboratory. The test results for geotechnical properties were used to develop the dam model, such as natural moisture content, sieve analysis, liquid limit, plastic limit, permeability, standard compaction test, consolidation test, and direct shear test. X-ray diffraction (XRD) test was carried out using Bragg-Brentano with a Bruker D8 advance machine to find out the crystalline materials in the soil used in the construction of the shell and core of the earth dam models in the hydraulics laboratory.

3. THERMAL PROPERTIES

3.1. Thermal conductivity

In the past, soil thermal properties were used to predict water, heat, and solute transport in soils (Abu-Hamdeh 2003). Among other essential thermal properties, soil thermal conductivity has a crucial role in temperature modeling in a porous medium. It depends on moisture content, mineral composition, temperature, and texture.
However, for low-density clay soils, the critical moisture content coincides with the plastic limit. The thermal conductivity of coarse-textured, angular grained soils is higher than that of fine-textured soils (Misra et al. 1995). Various authors have reported the thermal conductivity of soil at different temperatures and mineral compositions. For silty sand having quartz content of 64%, water content of 15%, and dry density of 1.77 g/cm³, reported thermal conductivity of 1.04 W/mK in the unfrozen state and 1.61 W/mK in the frozen state at –6 °C. (Chuvilin & Bukhanov 2019). The thermal conductivity of sand collected from two places had a value of 1.9, 1.25 at 20% water content. The thermal conductivity of saturated sand was 3.12 W/mK (Buntebarth 2020). The average water thermal conductivity value W/mK was 0.56 at 17 °C (Chuvilin & Bukhanov 2019). The thermal conductivity of water was reported to be 0.594 W/mK (Kosky et al. 2012).

3.2. Specific heat and volumetric heat capacity

‘Specific heat is the amount of heat required to change the temperature of a mass unit of a substance by one degree. In other words, the specific heat capacity of a substance is the heat capacity of a sample of the substance divided by the sample’s mass. It is used to calculate the energy change associated with a temperature change.’ Many factors influence soil heat capacity, among which water content and soil density are the key factors that influence it. In sandy soil, specific heat is associated with water content for known bulk density. Water in the liquid state has one of the highest specific heats, comparing with common substances. The specific heat of soil is determined using a calorimeter by measuring its heat capacity and dividing its mass (Kosky et al. 2012). The sum of volumetric heat capacities of each soil component multiplied by their fraction gives soil volumetric heat capacity. ‘It stands for stored internal energy ability of a given soil volume while undergoing a given temperature change.’ The analysis of coupled heat-water transfer in soil plays a vital role in the temperature and heat transfer within an earth dam. Various literature has mentioned specific heat and volumetric heat capacity, among which few are presented. Dry sand had specific heat of 932–958 J/kgK measured using a calorimeter (Ižvolt & Dobeš 2014). While specific heat of the sand, quartz, is 830 J/Kg.°C, dry soil is 800 J/Kg.°C and wet soil is 1,480 J/Kg °C, respectively. (Engineering toolbox 2003, Specific heat of some common substances). Kodešová et al. (2013) reported a soil’s specific heat of 0.73 kJ/KgK, and a volumetric heat capacity of 1.9 MJ/m³/K, at the dry density of 1.34 g/cm³. Specific heat of the water was 4.18 kJ/kgK and volumetric heat capacity was 4.18 MJ/m³/K. For clay of dry density 1.46 g/cm³, specific heat was 0.86 kJ/kgK and volumetric heat capacity was 2.30 MJ/m³/K. While specific heat of water was 4,190 kJ/kgK. And at 30 °C, the specific heat of the water was recorded as 4.1175 kJ/kgK or 74.181 J/(mol k) (Engineering toolbox 2004, water - specific heat).

4. HEAT TRANSFER IN SOIL

‘Heat transfer refers to thermal energy that passes between objects by either thermal conductivity, thermal convection, in which a fluid moves between regions of different temperature, or thermal radiation, in which energy is transmitted by electromagnetic radiation.’ Temperature difference induces a heat flux. This induced heat flux flows from the hotter medium to the colder; it requires a difference in the temperature and a medium through which heat flows. Heat flux also depends on the thermal transfer coefficient of soil used in constructing the earth dam and its foundation. In an earth dam, heat can flow through soil-to-soil particles (conduction) and fluids’ motion in the pores (convection). The air temperature surrounding the earth dam and water in the reservoir upstream of the earth dam serves as the dam’s principal thermal loading. Other sources that may affect the earth dam’s temperature variation are geothermal, a frozen process in colder regions, humidity changes around an earth dam, and wind influence. Tokoro et al. (2016) proposed a thermal conductivity model and empirical equations for soil. The thermal conductivity of soil and its moisture content had a non-linear relationship. Ižvolt & Dobeš (2014) monitored the impact on the measured value of three different building materials’ specific heat and thermal conductivity due to the calorimetry test procedure’s modification. Alim et al. (2017) used Seep/w to calculate seepage discharge for a homogeneous earth dam resting on an impervious base without any filter or clay core. They proposed an equation for seepage through a homogeneous earth dam resting on an impervious base.

4.1. Heat conduction

‘It is defined as the amount of heat passing in unit time through a unit cross-sectional area of the soil under a unit temperature gradient.’ Viscosity and water density are temperature-dependent phenomena in the earth dam,
which affect the heat conduction in the soil particles present in an earth dam’s body. Heat conduction can occur due to soil’s material property present in the earth dam body and foundation. Heat conduction is affected by the saturated/unsaturated region in the earth dam, as below the phreatic line, natural or free convection also occurs. Above the phreatic line, conduction predominates; that is, in the upper zone of the dam, there is pure heat conduction and no heat advection as negligible water flow is present above the phreatic line; hence, slow heat transport from the dam surface inward to the dam occurs. While in the central zone, both convection in x-direction and conduction in y-direction takes place.

4.2. Convection in soil
Convective heat transfer occurs in an earth dam whenever there is a difference in temperature in the earth dam body and the water upstream. Natural convection is produced by motion caused due to density difference in a fluid due to temperature difference, called convection currents. It continues as long as temperature difference exists in an earth dam and upstream water. Temperature acts as a natural tracer to find the seepage flow and water flux to localize leakage in embankment dams. In an earth dam, heat flux was used to detect leakage regions and determine seepage velocity using temperature observation. When seepage water goes through an earth dam’s pores, it exchanges heat with the adjacent soil medium (Cuong et al. 2017). Heat flux varies in an earth dam due to convective heat transfer, due to the energy transported by seepage flow. Increased fluid speed enhances high heat transfer in convection, and with high heat transfer, a high-pressure drop can be observed.

5. METHODOLOGY
The physical model was scaled down so that it was possible to perform experiments in the laboratory using a hydraulic flume. The length scale factor for the experimental model was 1/100. This scale factor was applied to the length, width, and height of the dam, and the discharge obtained. The effect of the longitudinal slope was studied by keeping these dimensions: upstream slope 38°, downstream slope 45°, bottom width 52 m; the height of the dam was kept at 20 m, while the longitudinal slope was varied at 0.00%, 6.07%, 2.28%, 4.00% slope for the models 1, 6, 7, 8 respectively. The effect of the central impervious core (clay) on water and heat flux was studied in models 9 and 10 by comparing with the homogeneous model (model 1). The dimensions of models 9 and 10 were similar to model 1 but with an impervious core of bottom width 18 m each and top width of 2.4 m and 1.9 m, respectively. Table 1 shows the different dimensions of the homogeneous earth dam models with their dimensions and upstream head. Table 2 shows an earth dam’s models with different horizontal filter lengths and a filter thickness of 3 m.

5.1. Experimental setup
An earthen dam of known dimensions was scaled down for experimental work; 16 earth dam models were constructed in a hydraulic flume of dimensions 300 cm length, 30.5 cm width, and 40 cm height. A Proctor penetrometer was used to control the compaction in layers of the earth dam during construction. The effect of scaling was considered as it affects the outcome of the result. A homogenous as well as an earth dam with central clay core was constructed. The temperature variation inside the dam was measured to calculate the heat flux across the earth dam in each model due to the convective water flow. Hydraulic flume was tilted to change

<table>
<thead>
<tr>
<th>Model number</th>
<th>Upstream water head (m)</th>
<th>Upstream slope (degrees)</th>
<th>Downstream slope (degrees)</th>
<th>Bottom width of the dam (m)</th>
<th>Height of dam (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.5</td>
<td>38</td>
<td>45</td>
<td>52</td>
<td>20</td>
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<tr>
<td>2</td>
<td>13.5</td>
<td>38</td>
<td>59</td>
<td>52</td>
<td>20</td>
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<tr>
<td>3</td>
<td>13.5</td>
<td>50</td>
<td>34</td>
<td>52</td>
<td>20</td>
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<td>13.5</td>
<td>50</td>
<td>34</td>
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<td>20</td>
</tr>
</tbody>
</table>
the longitudinal slope to study its effect on water flux and heat flux. Fluid viscosity was adjusted by adding sugar and then measuring the rotational rheometer, a viscosity measurement instrument, in the physics laboratory to study its effect on water flux and heat flux.

Proper compaction in an earth dam leads to increased stiffness and strength, minimizing the settlements and preventing the dam’s sliding failure. A Proctor penetrometer was used to achieve proper compaction in the construction of the 16 models of the earth dam. The soil was placed in five layers of 4 cm each at optimum moisture content with 90–95% variance using a Proctor penetrometer while keeping each layer’s penetration rate at 1.3 cm/s. An average of three penetration resistance were compared with the calibration chart of moisture-penetration resistance and moisture-density curve relationship. A longitudinal filter was provided, and its length was varied for studying its effect on water flux and heat flux. Models 14–16 were constructed with a downstream filter with varying lengths, as mentioned in Table 2. In the present study, the water flux was obtained from the seepage discharge calculation; while heat flux in models was calculated using temperature readings obtained by a digital thermometer in a hydraulic flume.

5.2. Numerical modeling
Geostudio 2020 software is one of the robust programs based on the finite element technique and can simulate and analyze water flux using Seep/w and heat flux using Temp/w. A finite element mesh of size 0.1 m was chosen after several trial computations by changing the mesh size. The mesh size was determined so that it doesn’t affect the computation time to a large extent and yields a good result.

6. RESULTS AND DISCUSSION
• The basic properties of soil were tested, and their results are shown in Table 3.

Figure 1 showing results of intensity vs. angle (2θ) for soil used in the construction of homogeneous earth dam models as well as in the shell of the earth dam in non-homogeneous earth dam models, while Figure 2 shows XRD results of intensity vs. angle (2θ) for soil used in the core of non-homogenous earth dam. Silicon oxide

| Table 2 | Earth dam models with different filter lengths |
| --- | --- | --- | --- | --- | --- | --- |
| Model number | Upstream slope (degree) | Downstream slope (degree) | Bottom width of dam (m) | Height of dam (m) | Length of the filter from the downstream end (m) | % length ratio of filter to the total length (m) |
| 1 | 38 | 45 | 52 | 20 | 0.0 | 00.00 |
| 14 | 38 | 45 | 52 | 20 | 15.5 | 29.80 |
| 15 | 38 | 45 | 52 | 20 | 23.0 | 44.23 |
| 16 | 38 | 45 | 52 | 20 | 13.0 | 25.00 |

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Name of the test</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural moisture content</td>
<td>1.49%</td>
</tr>
<tr>
<td>2</td>
<td>Specific gravity</td>
<td>2.57</td>
</tr>
<tr>
<td>3</td>
<td>Grain size distribution</td>
<td>Soil classification: Silty sand D₆₀: 1.61 D₅₀: 0.36 D₁₀: 0.09 Cₐ: 17.19 Cₑ: 0.87</td>
</tr>
<tr>
<td>4</td>
<td>Atterberg’s limit</td>
<td>Liquid limit: 26.24% Plastic limit: 12.69%</td>
</tr>
<tr>
<td>5</td>
<td>Compaction:</td>
<td>Dry unit weight of the soil: 18.05 kN/m³ Optimum moisture content: 13.10%</td>
</tr>
<tr>
<td>6</td>
<td>Permeability of soil (shell)</td>
<td>6.78 × 10⁻⁶ m/s</td>
</tr>
</tbody>
</table>
**Figure 1** | XRD of soil used in the shell of earth dam models.

**Figure 2** | XRD of soil used in the core of the earth dam models.

**Figure 3** | Water flux in model 1.
(SiO₂) was the primary chemical compound in the soil (shell) as the angle (2θ) was at 26.715 with an intensity of 100% and having the empirical formula of O₂Si. The h, k, and l were 0, 1, and 1 respectively, and spacing between planes (d) equals 3.33420 Å. In contrast, quartz was the primary chemical compound found in the soil (core), having the chemical formula SiO₂ and empirical formula O₂Si. The lattice's crystal system was hexagonal with an angle (2θ) of 26.64 at an intensity of 100%. h, k, l, of the lattice was 0, 1, 1 respectively, and spacing between planes (d) equals 3.34353 Å.

6.1. Contours of water flux and heat flux
The contours of water flux in m²/sec/m² are shown in Figures 3–18 for models 1 to 16, while heat flux is shown in Figures 19–34. The variation of water flux and heat flux for the location is shown. The earth dam model’s phreatic

![Figure 4](image1.png) | Water flux in model 2.

![Figure 5](image2.png) | Water flux in model 3.
**Figure 6** | Water flux in model 4.

**Figure 7** | Water flux in model 5.

**Figure 8** | Water flux in model 6.
Figure 9 | Water flux in model 7.

Figure 10 | Water flux in model 8.

Figure 11 | Water flux in model 9.
Figure 12 | Water flux in model 10.

Figure 13 | Water flux in model 11.

Figure 14 | Water flux in model 12.
Figure 15 | Water flux in model 13.

Figure 16 | Water flux in model 14.

Figure 17 | Water flux in model 15.
Figure 18 | Water flux in model 16.

Figure 19 | Heat flux in model 1.

Figure 20 | Heat flux in model 2.
Figure 21 | Heat flux in model 3.

Figure 22 | Heat flux in model 4.

Figure 23 | Heat flux in model 5.
line marked with a dotted line in its respective figure is also shown, which keeps the flow of heat and water below it.

- Figure showing the graph of heat flux is Figure 35, with its x-axis showing the number of earth dam models, and the y-axis denoting heat flux in kJ/sec/m². Figure 36 represents a water flux graph with its x-axis as the number of earth dam models, and the y-axis denotes water flux in m³/sec/m². While Figure 37 shows the flux on the y-axis to compare heat flux and water flux with the respective model shown on the x-axis.
- On increasing the downstream slope of an earth dam from 45 degrees (in model 1) to 59 degrees (in model 2), the water flux and heat flux increased by 34.81% and 34.37%. While increasing the downstream slope from 34 degrees (in model 3) to 45 degrees (in model 13), the water and heat flux increased by 42.36%.
- On increasing the upstream slope from 38 degrees (in model 1) to 45 degrees (in model 12); that is, 18.42%, the water flux and heat flux decrease by 0.34% and 0.99%, respectively. While increasing the slope from 38 degrees (in model 1) to 50 degrees (in model 13); that is, 31.57%, water flux and heat flux both decreased by 0.51%.
**Figure 26** | Heat flux in model 8.

**Figure 27** | Heat flux in model 9.

**Figure 28** | Heat flux in model 10.
On increasing the dam’s length from 52 m (in model 3) to 56 m (in model 4); that is, by 7.69%, the water flux and heat flux both had an insignificant reduction of 0.02%.

On increasing the earth dam’s height for the same upstream head by 33.33%; that is, 15 m (in model 5) to 20 m (in model 4), the water flux and heat flux remain unchanged.

On increasing upstream head of water from 13 m (in model 11) to 13.5 m (in model 1); that is, by 3.85%, the water flux and heat flux increased by 0.34%.
On increasing the longitudinal slope by 2.28% (in model 1 to model 7), water flux and heat flux both increased by 1.33%, and increasing longitudinal gradient by 4% (in model 1 and 8), water flux and heat flux increased by 2.01% and 2.06% respectively. While increasing slope by 6.07% (from model 1 to model 6), both water flux and heat flux increased by 2.55%.

With a decrease of the top width of clay core by 20.83% from model 9 to model 10, both the water and heat flux increase by 3.44%.

With the downstream filter of length 15 m in model 16, 15.5 m in model 14, and 23 m in model 15, water flux increased by 414.23%, 533.38%, and 666.51%, respectively, and heat flux increased by 414.23%, 533.38%, and 666.75% respectively.
7. CONCLUSION

Sixteen earth dam models constructed in a hydraulic flume were built to study the water flux due to seepage and heat flux due to the convective heat transfer in the respective earth dam models. Temperature measurements were done in the earth dam model placed in a hydraulic flume using digital thermometers to determine the heat flux and validate it with the simulation result of Temp/w in Geostudio 2020. Thus it concluded by observed near walls of a hydraulic flume, soil pores of the dam were of larger volume, resulting in an increased local water flow. Regional flow variation due to wall channeling led to enhanced convection heat transfer, hence increasing the temperature. By increasing the earth dam’s length, the heat and water flux had an insignificantly low reduction, and hence flux remained almost the same. With the increase in the dam’s height with the same upstream water head, the heat and water flux remained unchanged. Heat flux obtained was found to be a helpful alternative in detecting seepage and water flux in an earth dam. As temperature sensors are cheaper than the
Figure 35 | Heat flux in different models of an earth dam.

Figure 36 | Water flux in different models of an earth dam.

Figure 37 | Water and heat flux comparison in different models of an earth dam.
discharge and water flow measuring devices, it helps to detect water at a reduced cost compared to conventional devices and hence improves the benefit-cost ratio of the project.

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DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

REFERENCES


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