Carbon reduction effectiveness and efficiency of earth-berming design for speed skating ovals

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Abstract. Earth-berming design is a common energy-saving practice for speed skating ovals. This study explores the impacts of different earth-berming conditions on the carbon emissions during the operation phase of the venue and evaluates the carbon reduction efficiency by taking into account the incremental carbon emissions caused by the excavation during the construction phase. In this study, three different climate zones were selected as the study environment to simulate the carbon reduction effect of two basic forms of mainstream-scaled speed skating ovals under various earth-berming conditions and to summarise the fitting equations of carbon reduction efficiency. The study found that the total annual carbon emissions ($CE$) of both forms are the lowest in the severe cold zone in general, and the decreased carbon ($dCE$) from the earth-berming design positively correlates with the excavated volume ($V$) with a maximum value of 98.9 tCO$_2$e/y. Among all regions, the maximum $dCE$ for all forms is highest in the severe cold zone, 5.1% and 9.8% more than that in the hot-summer-cold-winter zone, which has the worst performances. The carbon reduction efficiency of the earth-berming design was measured by critical gain time ($T$). The earth-berming covariates and $T$ for both forms could be fitted by a quadratic equation, which showed that the larger the burial depth on the large-span space side of Form 1 compared to the auxiliary space side, the smaller the $T$-value, whereas the greater the $F$ of Form 2, the smaller the $T$-value.

1. Introduction

Global warming and the consumption of non-renewable energy make carbon neutrality increasingly important. According to the International Energy Agency (IEA), building operations account for 30% of global final energy consumption [1]. In China, public buildings which are characterized by high carbon intensity, accounting for 38.6% of the carbon emissions from the construction sector [2]. It shows that carbon reduction is important throughout the entire lifecycle of buildings. With the advancement of China’s ice sports promotion policies, the amount of speed skating ovals characterized by huge energy consumption will increase. Therefore, it is necessary to apply decarbonization techniques from the perspective of architectural design.

In the early design stage, earth-berming is considered an effective energy-saving method, and it has been applied in many completed projects. The Calgary Olympic Oval reduced the enclosure surface area exposed to the air for heat exchange by 30% [3]. The "Ice Ribbon" put 75% of the floor area underground to improve the overall energy efficiency of the building [4]. Among the 49 speed skating ovals in the world, nearly one-third were found to have adopted the earth-berming design. However, the increase in carbon emissions caused by earth-berming during the construction phase should not be ignored, and how to balance it with the carbon reduction in the operational phase is worth more consideration.

1.1. Energy saving of ice sports venues

Scholars have done a variety of investigations on energy conservation of ice sports venues, but most of the research target is ice hockey arena, which is on a smaller scale. The methods include applying residual temperature recirculating cavity envelope [5], using inflatable membrane structure [6], optimizing spatial scales and spatial combinations [7] and changing building forms [8].

1.2. Earth-berming and Energy-Saving

Many studies have proved the decarbonization effect of the earth-berming design. F Beigli and R Lenci (2016) found that earth-berming design positively impacts indoor thermal stability in Iran [9]. Liyan Song (2021) found the thermal stability of soil is a natural insulator and cold protector compared to conventional enclosures [10]. Boyuan Gong (2023) studied the total building energy consumption of a typical Turpan residence and found that the total building energy consumption decreased with the

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increase of buried depth [11]. C Cong et al. (2023) found a one-storey earth-bermed museum reduced the annual energy consumption by up to 488 MWh [12].

However, there is also a significant increase in energy consumption caused by excavation. Marco L Trani et al. (2016) studied a residential construction project in Milan with three underground floors, calculating that earthwork activities generated 28948.37 kg of CO₂ [13]. L Pinky Devi and Sivakumar Palaniswami (2017) found that the energy consumption from soil excavation and transportation generated energy consumption of 14-89 MJ/m³ and 19-135 MJ/m³, respectively through five cases [14].

1.3. Research Gap and Objective

Existing studies on energy-saving for ice sports venues focus on HVAC and material optimisation, which leads to very few studies on energy saving strategies in the early design stage. Moreover, most research objects are ice hockey venues rather than speed skating ovals. In addition, existing research on the decarbonization effects of earth-berming lacks a cross-life-cycle "input-benefit" correlation study.

In this study, we generate typical research models for mainstream-sized speed skating ovals; simulate the quantitative relationship between various earth-berming design options and decarbonisation effects; consider the carbon emission increment brought about by excavation in the construction phase and the carbon emission reduction in the operation phase and perform a fitting analysis to derive a benefit function. The results of this study reveal the impact of the earth-berming characteristic parameters on the carbon emissions during the operation phase of speed skating ovals and derive the most economical design scheme under the consideration of the additional carbon emissions increment from excavation.

2. Methodology

Figure 1 shows the research framework. Firstly, this study established the representative geometric model of mainstream-sized speed skating ovals and the simulated ground, and generated the energy consumption testing model further; secondly, the energy consumption simulation parameters were set according to spatial performance requirements and climate characteristics; then, the relationship between the testing models and the ground was continuously adjusted, and the performance of the energy consumption all testing models were recorded; finally, the results of the simulation were analysed [15].

As shown in Figure 2, the research models cover an area of 16000 m², with a total floor area of 17480 m². The sports space has a floor area of 13000 m², including a 400 m speed skating track that meets the International Skating Union (ISU) standards [16]. The internal space is divided into sports space, roof space, audience space and auxiliary space with different environmental characteristics, among which the sports space is subdivided into overhead space, racing space and rink space vertically. Two basic forms derive from the position of the sports field: Form 1 has the same elevation of the sports field as the floor slab of the auxiliary space, and in Form 2 it is the same as the first floor of the stand. The audience space has a 5-storey unilateral stand with the height of the first floor being 3 m. The auxiliary space is 6 m on the first floor and 5 m on the second floor. The height of the roof is 13.7 m. The building is east-west oriented and the rectangular volume (including the audience and auxiliary space) is on the south side. The testing models for the two forms without earth-berming are denoted as p₁s and p₂s.

The two long edges of the bottom of the main body of the venue are extended to form two parallel lines, and both of them are used to form a combined surface to simulate the ground through extrusion and release operations. The surface is determined by the burying depths d₁ and d₂ of the two long edges of the venue's main body. In Form1, 0<d₁<6, 0<d₂<6; in Form2, 0<d₁<3, 0<d₂<3. The two forms take the values within the above ranges with a step
size of 0.6m when generating the testing models, coming out of the testing model group 1 with 121 samples and group 2 with 36 samples, respectively.

![Diagram of energy model and testing model generation process.](image)

**Figure 2.** Diagram of energy model and testing model generation process.

### 2.3. Energy simulation parameter setting

#### 2.3.1. Calculation method of operational energy consumption

In order to eliminate factors other than the earth-berming parameters, the energy simulation model operating parameters and running schedule are unified according to the "2022 Special Regulations Technical Rules Speed Skating. FINAL" issued by the International Skating Union (ISU), "Code for Green Building Performance Calculation for Civil Buildings" (JGJ/T 449-2018), and "Code for Design of Sports Buildings" (JGJ 31-2003). Since the focus of this study is on the early design stage of the speed skating oval, the parameters of the building envelope simulation in different climate zones do not take into account the specific construction, and the lowest value in the "Code for Energy Efficiency and Renewable Energy Utilization in Buildings" (GB 55015-2021) is uniformly adopted. There is no national specification for the special design parameters of speed skating tracks, so they are set according to the statistical results of earlier studies and the current mainstream operation parameters. All testing models have the same track design. Table 1 lists the set parameters for the building envelope. Table 2 lists the set operation parameters for the building energy simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Roof U-value (W/m²·K)</th>
<th>External wall U-value (W/m²·K)</th>
<th>Ground floor R-value (m²·K/W)</th>
<th>External window U-value (W/m²·K)</th>
<th>SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harbin</td>
<td>0.25</td>
<td>0.4</td>
<td>1.1</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Beijing</td>
<td>0.4</td>
<td>0.55</td>
<td>0.6</td>
<td>2.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Wuhan</td>
<td>0.4</td>
<td>0.8</td>
<td>0.6</td>
<td>3.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

#### Table 1. Setting parameters for the building envelope.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Heating (℃)</th>
<th>Cooling (℃)</th>
<th>Humidity (%)</th>
<th>Occupancy (people/m²)</th>
<th>Lighting (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof space</td>
<td>——</td>
<td>——</td>
<td>30~65</td>
<td>——</td>
<td>——</td>
</tr>
<tr>
<td>Overhead space</td>
<td>16</td>
<td>22</td>
<td>30~65</td>
<td>——</td>
<td>——</td>
</tr>
<tr>
<td>Racing space</td>
<td>12</td>
<td>18</td>
<td>30~65</td>
<td>——</td>
<td>——</td>
</tr>
<tr>
<td>Rink space</td>
<td>-9</td>
<td>-5</td>
<td>30~45</td>
<td>0.03</td>
<td>48</td>
</tr>
<tr>
<td>Audience space</td>
<td>18</td>
<td>22</td>
<td>40~65</td>
<td>0.85</td>
<td>15</td>
</tr>
<tr>
<td>Auxiliary space</td>
<td>18</td>
<td>26</td>
<td>40~65</td>
<td>0.40</td>
<td>8.8</td>
</tr>
</tbody>
</table>

#### Table 2. Setting operation parameters for the internal environment.

The formula for calculating the annual carbon emissions of the building $CE$ (kgCO₂e/y) is equation (1):

$$ CE = EUI \times A \times OM $$  

(1)

The annual carbon reduction $dCE$ (kgCO₂e/y) for each undercut design testing model is calculated as equation (2):

$$ dCE = CE_s - CE_n $$  

(2)
where EUI (kWh/(m²·y)) is the energy use intensity, A (m²) is the energy simulation area of the energy model, CEs (kgCO2e/y) is the total annual carbon emission of the no-earth-berming scenario as the initial control model, CEn (kgCO2e/y) is the total annual carbon emission of each testing model. OM is the average carbon emission factor of 0.5703 kgCO₂/kWh for the current Chinese power grid [17].

2.3.2. Calculation method of carbon emission of excavation

Carbon emissions caused by excavation vary under various construction environments and construction methods. According to the calculation result of Xia Wang (2012) [18] and J Chou et al. (2013) [19], the average energy consumption of excavation and removal of earth varies from 32 kWh/m³ to 208.2 MJ/m³. In this paper, to make the research results more intuitive, the incremental energy consumption per cubic meter of excavation in China in 2012 is converted to current carbon emission efficiency, which is taken as \( \Delta E = 30 \text{kWh/m}^3 \) by comprehensively comparing with the results of other existing studies. The formula for calculating the annual carbon emission increment \( eCE \) (kgCO2e/y) from the excavation for each testing model is equation (3) where \( V \) (m³) is the excavated volume:

\[
eCE = \Delta E \times V \times OM
\]  

(3)

2.3.3. Calculation method of decarbonization efficiency

To characterise the decarbonisation efficiency of the earth-berming design more intuitively, this study introduces the critical gain time \( T \) (yr), which is calculated as equation (4):

\[
T = \frac{eCE}{dCE}
\]  

(4)

The value of critical gain time \( T \) indicates the time when the \( eCE \) and \( dCE \) are offset, and the speed skating oval will enter the "pure gain period" after \( T \) years.

3. Result

3.1. Overall energy performance in each climate zone

The two groups of testing models were substituted into the meteorological data of the three study regions to test the CE performance, and the distribution characteristics of the statistical results were obtained, as shown in Figure 3. The distribution domains of the \( CE \) values of both forms were the lowest in the severe cold zone, the second lowest in the cold zone, and the highest in the hot-summer-cold-winter zone; their median values were respectively 4390.83 tCO₂e/y, 4453.20 tCO₂e/y, 4467.99 tCO₂e/y and 4369.40 tCO₂e/y, 4433.50 tCO₂e/y, 4444.97 tCO₂e/y. The variance of \( CE \) thresholds was significantly higher in the severe cold zone than in other zones, indicating that in the severe cold region, the effect of decarbonisation is more sensitive to the change in the way of earth-berming.

3.2. Effect of earth-berming design on carbon emission benefits

Figure 4 shows the correlation analyses of the excavation covariates \( d1 \) and \( d2 \), \( d1-d2 \) characterising the slope of the ground, the total excavated volume \( V \), the annual carbon reduction \( dCE \) and the critical benefit time \( T \) for each form in each climate zone. The results indicates that both groups of testing models have the strongest correlation with \( V \) and a weaker correlation with the \( d1-d2 \) difference. Figure 5 further demonstrates that the relationship between \( dCE \) and \( V \) is a fluctuating positive correlation state. Generally, the \( dCE \) increases aligned with \( V \), but the \( dCE \) caused by the slope of the ground varies under a similar volume. The maximum \( dCE \) of Form 1 and Form 2 among the three zone is 2.2% and 1.1% of total \( CE \), respectively, the amount can be up to 98900.11 kgCO2e/y and 47684.41 kgCO₂e/y, offsetting the \( CE \) from all the non-sports spaces.

For the critical gain time \( T \), both \( V \) and \( dCE \) of Form1 have a low correlation with it, while \( d1-d2 \) characterizing the ground slope has a strong correlation, and the correlation strength decreases from the severe cold, cold and then hot-summer-cold-winter zones in order. In contrast, in the case of Form 2, the ground slope is less influential on \( T \) than in Form 1, but the negative correlation of \( dCE \) and \( V \) with \( T \) values is significantly stronger. The influence of \( V \) is strongest in hot-summer-cold-winter zones, while the influence of \( dCE \) is strongest in severe cold zones.
3.3. Prediction of decarbonization efficiency for earth-berming

In order to further explore the complex relationship between earth-berming and $T$ to provide an estimation tool, the covariates $d_1$, $d_2$ and $T$ are fit in equation (5), which directly characterise the relationship between the building and the ground, and the results are shown in Figure 6.

$$T = a 	imes d_1^2 + b 	imes d_2^2 + c 	imes d_1 \times d_2 + e \times d_1 + f \times d_2 + k \quad (5)$$

The values of the coefficients $a$, $b$, $c$, $e$, $f$, and $k$ in each case are shown in Table 3. The adjusted $R^2$ of this fitting equation reaches 0.811–0.917, which shows that it has a high degree of fit and good accuracy in practical application. For Form 1, the top 10 shortest $T$-values in all climatic zones are kept with $d_1=0$ m and $d_2$ taking values within 0.6–6 m. The minimum value of $T$ is 12.41 yr from the severe cold zone. When the largest carbon reduction is adopted, i.e., $d_1$ and $d_2$ both obtain the maximum value of 6, the $T$-values of the three zones are 16.61 yr, 18.13 yr, and 17.46 yr, slightly lower than the median. Meanwhile, for similar $V$, the $T$ values increase with the increase of $d_1$-$d_2$. For Form 2, the $T$ reach the lowest values of 16.49 yr and 20.71 yr, respectively, in the severe cold and cold zones, when $d_1=0$ m and $d_2=3$ m. When the $d_1$ and $d_2$ take the maximum values of 3 m, the $T$-values are 19.05 yr and 21.41 yr, higher than the median in each group. In the hot-summer-cold-winter zone, the scenario with the lowest $T$-value is when $d_1$ and $d_2$ reach the maximum value of 3 m, when the $T$-value is 20.92 yr.
4. Discussion

4.1. Interpretation of main findings and study implications

This study addresses the need for research on the impacts of earth-berming design for speed skating ovals on carbon emissions and carbon reduction benefits, which has reference significance for future practices in China. First, it was found that the annual total CE decrease with increasing V in all conditions, and the CE of Form 1 is overall higher than that of Form 2. Regardless of the forms, the CE is the lowest in the severe cold zone. Second, the carbon reduction effect from earth-berming is more pronounced in the severe cold zone, and the change in the dCE due to the ground slope is more pronounced than in other climate zones. In addition, in Form 1, the greater the burial depth of the non-auxiliary space side relative to the other side under similar V, the shorter the time of critical gain. In Form 2, the smaller the V, the longer the T, and this phenomenon is especially obvious in hot-summer-cold-winter zone.

The results of this study are practical to the design practice of speed skating ovals. Firstly, it can guide the low-carbon design in different climate zones in China and help architects make choices in site selection. Secondly, this study also provides a formula for evaluating the carbon reduction benefits so that architects can estimate the total carbon emissions and decarbonisation efficiency by substituting architecturally operational variables and avoiding over-designing based on empiricism. Finally, the technical framework of this study is also applicable to similar sports building designs to assess the impact of earth-berming design on energy saving and decarbonisation.

4.2. Limitations and future work

In order to make the conclusions more intuitive, this study uses a constant to estimate the carbon emissions per unit volume increment brought about by excavation. In future research, the impact of different construction techniques, environment and building structure on the carbon emission increment will be considered to obtain the critical gain time, and self-generated methods will carry out the optimisation of low carbon emission construction.

Table 3. Coefficients of fitting equation.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Harbin Form 1</th>
<th>Harbin Form 2</th>
<th>Beijing Form 1</th>
<th>Beijing Form 2</th>
<th>Wuhan Form 1</th>
<th>Wuhan Form 2</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>-0.11048</td>
<td>-0.10473</td>
<td>-0.07621</td>
<td>-0.1063</td>
<td>0.27983</td>
<td>0.60485</td>
</tr>
<tr>
<td>b</td>
<td>0.27159</td>
<td>0.24028</td>
<td>0.16618</td>
<td>3.06066</td>
<td>2.21957</td>
<td>1.58476</td>
</tr>
<tr>
<td>c</td>
<td>-0.06245</td>
<td>-0.04633</td>
<td>-0.03817</td>
<td>1.71378</td>
<td>1.90878</td>
<td>1.79981</td>
</tr>
<tr>
<td>e</td>
<td>1.65134</td>
<td>1.38784</td>
<td>0.96749</td>
<td>-2.73729</td>
<td>-5.19171</td>
<td>-6.64441</td>
</tr>
<tr>
<td>f</td>
<td>-2.25792</td>
<td>-1.83075</td>
<td>-1.10832</td>
<td>-17.02155</td>
<td>-13.62064</td>
<td>-10.35118</td>
</tr>
<tr>
<td>k</td>
<td>16.80659</td>
<td>17.70851</td>
<td>16.49139</td>
<td>39.03791</td>
<td>40.85425</td>
<td>38.45486</td>
</tr>
<tr>
<td>R²</td>
<td>0.91666</td>
<td>0.89094</td>
<td>0.85675</td>
<td>0.81111</td>
<td>0.81363</td>
<td>0.82489</td>
</tr>
</tbody>
</table>
solutions, substituting the results of which into the current research framework will further improve the accuracy and practicability of the prediction model.

5. Conclusions
This study summarises two mainstream-sized speed skating oval forms, uses ladybug + honeybee plug-ins to calculate the impact of earth-berming on operational carbon emissions and excavation carbon increments, and compares the carbon reduction effect and efficiency of the two forms under different climatic conditions. The main conclusions are as follows:

(1) From 3.1, the $CE$ decreases with increasing $V$ and the $CE$ of Form 1 is generally higher than that of Form 2. The $CE$ of both forms is the lowest in the severe cold zone and the highest in the hot-summer-cold-winter zone, indicating the former is the best construction site for speed skating ovals.

(2) From 3.2, the maximum $dCE$ of Form 1 in the severe cold region is 5.1% more than the hot-summer-cold-winter zone, and in Form 2, the value is 9.8%. To shorten the $T$, Form 1 should bury the side of the large space deeper relative to the other side, and Form 2 only needs to increase the volume of excavation to achieve a better carbon reduction effect and efficiency.

(3) From 3.3, a quadratic equation can express the carbon reduction efficiency of both forms in all climate zones. The difference in the $T$-values in Form 1 is much smaller than Form 2. The minimum $T$-value of Form 2 reaches more than 19 yr, significantly higher than that of most scenarios of Form 1. However, some low-level venues often adopt Form 2, if we want to obtain carbon reduction benefits, we should maximise the operation time after completion rather than being easily abandoned.

Acknowledgments
This work was financially supported by the Key Research and Development Plan of Heilongjiang Province "Research and development of an intelligent cloud platform technology for monitoring carbon emissions from urban buildings in cold regions based on digital technology" (2022ZX01A33) and National Natural Science Foundation of China (NSFC) project "Design Theory and Method of Sustainable Intelligent Lunar Research Station" (52238002).

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