Survivability Optimization of the Silo Group Deployment by Agent Modeling and Simulation

Dai Haifeng
Xi'an High-tech Research Institute
Xi'an710025, China
e-mail: 3215692946@qq.com

Qi Changxing
Xi'an High-tech Research Institute
Xi'an710025, China

Bi Yiming
Xi'an High-tech Research Institute
Xi'an710025, China

Zhang Shutao
Xi'an High-tech Research Institute
Xi'an710025, China

Abstract—Survivability is an important indicator for the nuclear weapon deployed by silo group. From the viewpoint of survivability optimization, firstly, a brief analysis for A-side factors, B-side factors and environmental factors that influence survivability of the silo group is completed, extract the main factors and make corresponding limitations. Secondly, agent modeling method is introduced to establish the silo agent model, detail the model rules, analyze the changes in the deployment status of the silo group using the Markov process, and construct an objective function model for the optimization of the silo group survivability. Finally, simulation based on the objective function is performed, and the simulation result shows that the problem of survivability optimization deployment of the silo group get some sort of solution, which may provide reference for similar military target deployment problems.

Keywords—Silo Group Deployment; Survivability; Optimization; Agent Modeling and Simulation

I. INTRODUCTION

Looking at the development trajectory of the nuclear countries in the world and increasing the overall deterrent capability and the second counterattack capability of nuclear weapons have always been a major trend for the research and development of nuclear weapons in various countries. The overall deterrent capability, in turn, depends to a large extent on reliable secondary counterattacks. In order to improve the ability to counterattacks twice, one side must ensure that after the first wave of attacks by the enemy, it can still retain enough nuclear weapons. This makes the survivability of nuclear weapons an important indicator of the effectiveness of nuclear weapons. Silo-based nuclear missile silo also place great emphasis on survivability. During the Cold War between the United States and the Soviet Union, both countries invested a lot of manpower and material resources to upgrade the silos and improve the protection capabilities of the silos in technical point of view. But with the arrival of the bottleneck of the silo reinforcement technology and the constant renewal of the enemy's attack means that this idea is considered to be extremely low cost-effectiveness ratio and extremely passive[1-2]. As a result, the cluster deployment pattern of silos has attracted more attention.

II. FACTOR ANALYSIS AND LIMITATION

A. Analysis of Influencing Factors on Survivability of the Silo Group

The silo group survivability refers to the ability of nuclear missile silos to maintain technical and tactical performance in a specific battlefield environment and under attack conditions. The core of the silo group survival is the survival of nuclear missile the silo group. The factors that affect the survivability of the silo group are complex and diverse. Both static and invariable, real-time updates, man-made and objective. It can be summed up in three categories: A-side factors, B-side factors and environmental factors (A-side is the side to deploy the silo group and B-side is the side to attack the silo group).

A-side factors. Including the method of the silo group deployment, the proportion, structure and scale of the real and false targets within the silo group, the camouflage level, the engineering protection capability, the force's rapid response ability and the readiness level, etc. B-side factors. It is mainly B-side's reconnaissance ability and strike ability. The stronger the reconnaissance ability and the strike ability of B-side is, the more detrimental to the survival of the silo group. Environmental factors. It mainly includes weather, topography, electromagnetic environment and so on. In general, weather conditions with low visibility and complex topographic features are helpful to improve the survivability of silo group.

B. Limiting factors

In order to study the deployment of silos in the silo group and improve the survivability of the silo group, some factors must be limited.
Limiting B-side’s reconnaissance measures. The reconnaissance methods that B-side may take mainly include: close to reconnaissance, aerial reconnaissance and satellite reconnaissance. Although close to reconnaissance can obtain the most accurate information, while the fact that the silo group is located in the territory of A-side and is heavily guarded, it is dangerous and difficult for the enemy to infiltrate and carry out reconnaissance activities; the method of aerial reconnaissance is better in flexibility and pertinence, but the B-side detectors rely on the platform (mainly reconnaissance aircraft). Under the condition that the A-side air defense system is complete and the wartime is highly guarded, the B-side platform is difficult to penetrate and the reconnaissance cost is relatively high. The accuracy of satellite reconnaissance is not so high, but it has the advantage of accumulation of reconnaissance information for fixed targets, and the security of the platform is better. The analysis believes that the satellite reconnaissance threat is the most important and most realistic threat. The reasons are as follows: First, the B-side satellite reconnaissance technology is increasingly advanced, and some satellites have an accuracy of 0.1 meters. Second, the number of B-side satellites is huge and military and civilian satellites can be mobilized to carry out intensive reconnaissance activities when necessary. Therefore, the B-side’s reconnaissance method is limited to satellite reconnaissance.

Limiting B-side’s attack methods. Possible attack methods that B-side may take against A-side’s silo group mainly include: air-drop drilling of ground bombs, precision guided attack outside the defense zone, and nuclear missile attack. Among them, the method of air-dropping ground-bombing is highly targeted and has a good destruction effect. However, the B-side platform is also threatened by the A-side’s air-defense system, which poses a greater risk of action. The method of accurate guided attack, although highly safe, However, when A-side deploys anti-missile weapons in key areas, its attack effect will be reduced and the cost will increase [3]. Although the accuracy of nuclear missile attack is poor, it has a long range and a good damage effect. It is not easily intercepted by B-side. After analysis, it is considered that the B-side nuclear missile attack is the most important attack method. The reasons are presented. First, the B-side rocket carrier technology and guidance control technology are increasingly advanced, and the accuracy of hitting can be further improved. Secondly, nuclear missile attacks have a good effect on the damage, and underground targets can also be subjected to a nuclear-burst attack, which poses a greater threat. Finally, the silo group deployment areas are mostly away from densely populated areas, which can reduce collateral damage and humanitarian pressure from the nuclear missile attack. Therefore, the B-side attack is limited to nuclear missile attacks.

Limiting environmental factors. The environmental conditions do not take into account the effects of weather (the silo groups are not deployed in areas with extremely bad weather) and are set as common weather. The landforms are briefly divided into three categories: open areas, jungle lands and mountain forest lands.

According to the above assumption, the survival confrontation problem of the silo group has been simplified, laying the foundation for the modeling of the later.

III. MODELING

A. Silo Agent Modeling

Agent modeling is one of the commonly used methods for bottom-up modeling of complex systems. It can analyze the operating mechanism and emerging characteristics of complex systems and is widely used in the fields of economy, military, and management [3-5].

For the silo group survivability agent modeling, the silos in the silo group are first divided into three categories, namely real silos, empty silos and false silos. Among them, real silos are silos that have launching capabilities and are equipped with nuclear missiles; empty silos have launching capabilities but there are no nuclear missiles in silos, which can be considered as spare silos for real silos; and false silos are silos that do not have launching capabilities. They are purely false targets. When a nuclear missile is moved from a real silo to an empty silo, the original real silo becomes an empty silo, and the empty silo becomes a real silo. Overall, this movement will not change the number of real silos and false silos, but it will change the distribution of real silos and empty silos in the silo group. At the same time, in order to achieve better shielding effect, the position of the false silos need to be adjusted. It can be imagined that when there are a large number of silos in the silo group, the conversion of such real silos and empty silos is very complex, and the distribution of points brought about by this is also very complicated.

In order to facilitate the study, it is considered that each silo (including real silos, empty silos, and false silos) in the silo group is an agent that can move in point, and the missile's moving process can be characterized by the movement of the agent. The movement of the silo is used to describe the movement of the missile and the changes in the position of the real silo and the empty silo. The establishment of silo agent model is shown in Fig. 1.

![Fig. 1 Agent model](image-url)

In a grid coordinate system, The position of any silo \( i \) in a silo group in the moment \( t \) is expressed as \( W_{r}(x_{i},y_{i}) \). and define the movement rules of the agent as follows: Each agent can only move one grid to the neighboring grid within one beat (it can also remain still). If it moves up one grid, the new position is \( W_{r}(x_{i},y_{i}+1) \). Similarly, the downward direction is \( W_{r}(x_{i},y_{i}-1) \), the right is \( W_{r}(x_{i}+1,y_{i}) \), the left is \( W_{r}(x_{i}-1,y_{i}) \), the upper right is \( W_{r}(x_{i}+1,y_{i}+1) \), the lower right is \( W_{r}(x_{i}+1,y_{i}-1) \), the upper left is \( W_{r}(x_{i}-1,y_{i}+1) \),
the lower left is \( W_{t+1}(x,y) \) \( = W_{t}(x,y) \cdot P_{i}^{h} \) There can be no other agents in each of the eight neighboring cells of each agent. That is, there must be at least one space between any two silos (to prevent B-side’s one missile from destroying two silos at the same time); all agents are only required to move within the deployment areas.

Through the above analysis, the movement of each agent has the following characteristics: The status of the next beat of the silo agent is related only to its current status, and has nothing to do with the status of the previous beat, that is, it has no aftereffect, so the law of agent’s movement can be approximated as the Markov process \([6]\) on a two-dimensional plane, shown in Equation (1).

\[
P \{ W_{t+1} = K_{t+1} \mid W_{t} = K_{t}, \ldots, W_{i} = K_{i} \} = P \{ W_{t+1} = K_{t+1} \mid W_{t} = K_{t} \} \] (1)

In Equation (1), \( W_{t} \) is the status of distribution at the moment \( t \), \( K_{t} \) is the status of the agent at the moment \( t \). Since each agent’s next position status space has 9 elements (constraints are not considered here), denoted as \( \{ n_{0}, n_{1}, \ldots, n_{9} \} \), these 9 status will be based on the current position of the silo agent \( W_{t}(x,y) \). Corresponding to a position coordinate in the plane \( (x,y) \), so its one-step transition probability is described as Equation (2).

\[
p_{t} = \{ p_{n_{0}}, p_{n_{1}}, \ldots, p_{n_{9}} \} \] (2)

For all agents in the entire silo group, on the basis of the above mobility rules, the constraints of not exceeding the specified range and at least one grid interval between two adjacent agents are added. The one-step transition probability of all agents in the silo group is described as a set, shown in Equation (3).

\[
p = \{ p_{1}^{h}, p_{1}^{k}, \ldots, p_{9}^{h}, \ldots, p_{9}^{k} \} \] (3)

In Equation (3), \( k_{i} \) is the number of elements for silo \( i \) in the next status space, \( S \) is the total number of silos in the silo group, according to the characteristics of the Markov process. The next status of a certain silo \( i \) is shown in Equation (4).

\[ W_{t+1}(x_{i},y_{i}) = W_{t}(x_{i},y_{i}) \cdot p_{i}^{h} \] (4)

Assume that the current status of the silo group is Equation (5).

\[
Q_{t} = [W_{t}(x_{1},y_{1}), W_{t}(x_{2},y_{2}), \ldots, W_{t}(x_{i},y_{i}), \ldots, W_{t}(x_{j},y_{j})] \] (5)

The next status of the silo group is shown in Equation (6).

\[
Q_{t+1} = [W_{t+1}(x_{1},y_{1})p_{1}^{h}, W_{t+1}(x_{2},y_{2})p_{2}^{h}, \ldots, W_{t+1}(x_{i},y_{i})p_{i}^{h}] \] (6)

The number of next status \( Q_{t+1} \) is \( \prod_{i=1}^{s} k_{i} \).

B. Silo group survivability optimization modeling

The survivability optimization problem of the silo group is to maximize the preservation of nuclear missiles in the silo group. Assume the nuclear missile number in a silo group is \( N \) (real silos number are also \( N \)), the number of empty silos is \( M \). Number of false silos is \( F \), and use \( H \) indicates the number of nuclear missiles survived by B-side’s attack. The survivability of the silo group is usually measured in the form of probability. The survivability of the silo group is shown in Equation (7), (8) and (9).

\[
P = \frac{H}{N} \] (7)

\[
H = \sum_{i=1}^{s} n_{i} = \begin{cases} 0, & P_{i} \leq P_{0} \\ 1, & P_{i} > P_{0} \end{cases} \] (8)

\[
P_{i} = 1 - P_{i} - P_{ST} - P_{G/S} - P_{D/G} \] (9)

In Equation (7), (8) and (9), \( n_{i} \) is the judge value of the real silo; \( P_{i} \) is the survival probability of real silo \( i \); \( P_{0} \) is the probability threshold to judge the real silo survive or not; \( P_{i} \) is the real silo’s detected probability; \( P_{ST} \) is the real silo’s probability of being identified and detected; \( P_{G/S} \) is the real silo’s probability of being attacked and identified; \( P_{D/G} \) is the real silo’s probability of being destroyed and attacked, and \( P_{i} \), \( P_{ST} \), \( P_{G/S} \), \( P_{D/G} \) are all in the value range of \([0, 1]\).

Analysis believe that the probability of real silo being detected and the probability of being destroyed and attacked both have nothing to do with the existence of empty and false silos. The former depends on whether the B-side’s satellite scans the real silo, and the latter depends on the B-side weapon’s attack ability and the A-side real silo’s protection capabilities. Therefore, the A-side real silo is basically in the case of unchanged parameters, the former depends on B-side’s reconnaissance strength and environmental protection, while the latter depends on B-side’s attack strength and environmental protection. For the strength of B-side’s reconnaissance and attack, according to expert experience, the two may be blurred. The three descriptions and three quantized values corresponding to them shown in Table I and Table II.

| Reconnaissance Strength | \( P_{i} \) value | description (the number of satellites to reconnaissance) |
|-------------------------|------------------|--------------------------------------------------------|
| Low                     | 0.47             | 1-2                                                   |
| medium                  | 0.63             | 2-8                                                   |
| higher                  | 0.88             | 9 and above                                           |
The strength of cooperation or competition affects the B-side force; between the real silo show as competitiveness force, and factor false silo's camouflaging levels, all to increase similarity. So when cooperation and negative value when competitiveness and landform, Table III. deployment landforms, the values of the factors are shown in Table III.

**TABLE III. VALUES OF VARIOUS INFLUENCE FACTORS**

| Deploy landform   | Detecting factors | Identifying factors | Attack Factor | Damage Factor |
|-------------------|-------------------|---------------------|---------------|---------------|
| open areas        | 0.97              | 0.99                | 0.94          | 0.98          |
| jungle lands      | 0.63              | 0.71                | 0.93          | 0.86          |
| Mountain forest   | 0.53              | 0.56                | 0.91          | 0.44          |

Therefore, after considering the influence of topography and landform, $P_{m}$ and $P_{D/G}$ change to $P'_{m} = P'_{D/G} = \theta$. In addition, it is considered that after B-side identifies the A-side's real silos, whether attack or not to consider only the topographic factors, refer to the factors $\eta$ in Table III, so $P'_{G/S} = P_{G/S} \cdot \eta$.

For equation (2), Assume the following analysis: It is assumed that all empty silos and false silos in the silo group have a cover effect on the real silo and show as cooperative force; between the real silo show as competitiveness force, and the strength of cooperation or competition affects the B-side identification, and this impact can be characterized as a competitive or cooperative factor $\alpha$. $\alpha$ get positive value when cooperation and negative value when competitiveness [1–6]. In addition, it is assumed that the similarities between empty silos and real silos in the silo group are greater than the similarities between false silos and real silos, showing a greater cooperation force, and the camouflage level of real silos and empty silos is a pair of interrelationships with the false silo's camouflage levels, all to increase similarity. So factor $\alpha$ is shown in Equation (10), (11) and (12).

\[
\alpha_{M-S} = \sum_{m=1}^{M} \beta_{1} \frac{Y_{m} Y_{i}}{D_{mi}}
\]  

\[
\alpha_{F-S} = \sum_{f=1}^{F} \beta_{2} \frac{Y_{f} Y_{i}}{D_{fi}}
\]  

\[
\alpha_{N-S} = -\sum_{n=1}^{N} \beta_{3} \frac{Y_{n} Y_{i}}{D_{ni}}
\]  

In Equation (10), (11) and (12), $\alpha_{M-S}$, $\alpha_{F-S}$ and $\alpha_{N-S}$ representation of competition or cooperation factor that all empty, false and other real silos to the real silo $i$; $\beta_{1}$, $\beta_{2}$ and $\beta_{3}$ are the factor affecting the degree of competition or cooperation from terrain and landform; $Y_{i}$ and $Y_{n}$ are the camouflage level for silo $i$ and $n$; $Y_{m}$ is the camouflage level for empty silo $m$; $Y_{f}$ is the camouflage level for false silo $f$; $D_{mi}$ is the distance between empty silo $m$ and real silo $i$; $D_{fi}$ is the distance between false silo $f$ and real silo $i$. $D_{ni}$ is the distance from real silo $i$ to other real silos. The probability that real silos are identified after being detected becomes Equation (13).

\[
P'_{S/T} = P_{S/T} \cdot \pi \left( \alpha_{M-S} + \alpha_{F-S} - \alpha_{N-S} \right)
\]  

\[
= P_{S/T} \cdot \pi \left( \sum_{m=1}^{M} \beta_{1} \frac{Y_{m} Y_{i}}{D_{mi}} + \sum_{f=1}^{F} \beta_{2} \frac{Y_{f} Y_{i}}{D_{fi}} - \sum_{n=1}^{N} \beta_{3} \frac{Y_{n} Y_{i}}{D_{ni}} \right)
\]  

In Equation (13), $\pi$ is the recognition factor from terrain and landscape recognition; the value of $\alpha_{M-S} + \alpha_{F-S} - \alpha_{N-S}$ is limited in $[0, 1]$.

Based on the above analysis, the survivability Equation (9) is improved to Equation (14).

\[
P'_{T} = 1 - P'_{S/T} \cdot P_{G/S} \cdot P'_{D/G} = 1 - P_{T} \cdot \theta \cdot P_{G/S} \cdot \pi \cdot \left( \alpha_{M-S} + \alpha_{F-S} - \alpha_{N-S} \right) \cdot P_{D/G} \cdot \eta \cdot P_{G/S} \cdot \omega
\]  

The objective function of silo group survivability optimization is to obtain $P'_{T}$ (the maximum value of $P'_{T}$) When the number of real silos in a silo group is fixed, the objective function is equivalent to obtain the maximum value $H_{max}$.

**IV. MODEL SIMULATION AND RESULT ANALYSIS**

According to the agent model and optimization model established above, the agent simulation flow based on silo group survivability optimization is designed as shown in Fig.2. The main input parameters are the proportion, number, and initial distribution of silos in the silo group, agent parameters, B-side reconnaissance and attack conditions, deployment terrain, simulation times, and the number of simulated agent movements per simulation.

**A. Simulation**

Using the Anylogic8.2.3 software platform, a simulation model is set up, where the input parameters are set as follows: There are 12 real silos, 13 empty silos, and 7 false silos in the silo group. The initial distribution is shown in Fig.3 (Z in the figure represents the real silo and K represents the empty silo. J represents the false silo). The level of reconnaissance strength and attack strength of B-side is medium, and the

**TABLE II. ATTACK STRENGTH AND DESCRIPTION**

| Attack strength | $P_{n}$ value | description |
|-----------------|---------------|-------------|
| Low             | 0.56          | 1           |
| medium          | 0.71          | 2           |
| higher          | 0.94          | 3 and above |
simulation times is 100. The number of movements of each simulated agent is divided into two levels, 1000 and 2000. The deployment terrain is divided into three kinds (open areas, jungle lands and mountain forest lands). The simulation results are shown in Table IV.

The distribution of silo group survivability optimized for each group of experiments is shown in Fig. 4 and Fig. 5.

| Landform | Simulation Times | Number of Beats in Each Simulation | Average Number of Beats to Optimization | Survivability |
|----------|-----------------|-----------------------------------|----------------------------------------|---------------|
| Open     | 100             | 1000                              | 74                                     | 0.641         |
|          | 100             | 2000                              | 128                                    | 0.688         |
| Jungle   | 100             | 1000                              | 407                                    | 0.763         |
|          | 100             | 2000                              | 565                                    | 0.821         |
| Mountain | 100             | 1000                              | 633                                    | 0.874         |
| Forest   | 100             | 2000                              | 649                                    | 0.892         |

Assuming that the jungle land is a more complex landform than the open land, and the mountain forest land is a more complex landform than the jungle land, then according to the results of the optimized distribution of the landforms in Table IV, it can be seen that with the complexity of topography and landform, the average number of beats required to achieve an optimal distribution increases, and the probability of survival is higher when the optimization distribution is finally achieved. Looking at Fig. 4 and Fig. 5, as topography and geomorphology become more complex, the distribution of silos in the silo group tends to spread evenly across the surface evenly distributed, which explain that deploying silo group in open areas should be deployed in a planar manner, while in complex terrain and landscapes, deployment in strips is conducive to improving survivability.

**B. Analysis of Simulation Results**

Comparing Fig. 3, Fig. 4 and Fig. 5, it can be seen that the initial distribution of silos in the silo group is approximately a cluster distribution, but after the simulation, the distribution of silos in Fig. 4 and Fig. 5 tend to be evenly distributed, and this is a change of entropy increasing. It shows that the overall distribution of different types of silos in the form of cross-mixing is beneficial to the improvement of the survivability of the silo group.

Comparing the two sets of experiments shown in Fig. 4 and Fig. 5, and comparing the data in Table IV, it can be seen that comparing 2000 times to 1000 times, the average number of beats needed to reach the optimal distribution is larger, and finally reaches the optimal distribution. The higher survival probability indicates that the agent’s moving number of beats objectively limits, the optimal distribution that the simulation experiment can achieve. It can be imagined that if the simulation times is increased, the optimal distribution of the survivability of the silo group may also be updated.

**V. Conclusion**

The simulation results show that the method of agent modeling and simulation can be used to obtain a plan to deploy the silo group in different terrains to optimize the survivability. It has guiding significance for the deployment of the silo group, and this method of using agent modeling to find the optimal deployment problem can be extended to similar military deployment research.

It must be pointed out that, first of all, the research in this paper has some artificial restrictions on the terrain environment and agent rules. It only considers a certain single terrain, and does not involve multiple terrain crossover situations. Secondly, the proposed silo model in this paper is not really an agent. It is only a mobile semi-autonomous force model. Its movement rules are also a blind exploration, an exhaustive selection method, which results in experimental redundancy. Finally, this paper only studied the distribution...
of silos within a single silo group and did not consider the situation of multiple silo groups.

Fig. 4 The simulation result in 100 times and 1000 beats each time

Fig. 5 The simulation result in 100 times and 2000 beats each time

REFERENCES

[1] Nederveen Gilles Van. Shield of dreams: missile defense and U.S.-Russian nuclear [J]. Air & Space Power Journal, 2012, 26(3): 105-117.

[2] Howes R H, Place R L. Assessment of the survivability of communication systems for silo-based missile[J]. IEEE Technology and Society Magazine, 1989, 8(3): 7-10.

[3] Dane M Kuiper, Rym Z Wenkstern. Agent vision in multi-Agent based simulation systems[J]. Autonomous Agents and Multi-Agent Systems, 2015, 29(2): 161-191.

[4] TEDESCHI G, IORI G, GALLEGATI M. Herding effects in order driven markets: the rise and fall of gurus[J]. Journal of Economic Behavior & Organization, 2012, 81(1): 82-96.

[5] Michael P Wellman1. Putting the agent in agent-based modeling[J]. Autonomous Agents and Multi-Agent Systems, 2016, 30 (6): 1175-1189.

[6] Jane M Hawkins. Markov process models of the dynamics of HIV reservoirs[J]. Mathematical Biosciences, 2016, 275 : 18-24.

[7] Kaushik Mondal, Arindam Karnakar, Partha Sarathi Mandal. Path planning algorithm for mobile anchor in connected sensor networks[J]. Lecture Notes in Computer Science, 2015, 8956(1): 193-198.