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Modeling Runway Damage and Repair using the Simulation of Linear Interdiction, Cratering, and Repair (SLICR) Model

73rd MORS Symposium

June 23, 2005

William Todd, Allen Harvey and Frank Lewis
(SAIC) (SAIC) (OSD/PA&E)

Objective and Approach

Objective:

Develop methodologies to determine effectiveness of a multiple sub-munition attack against runways.

Approaches:

- Statistical analysis to provide heuristic model
- Monte Carlo simulation (SLICR model)

Contents

- ⇒ • Problem description
- Runway closing heuristic/ Statistical model
- SLICR model description and methodology
 - Probability of closing runway
 - Target flexibility
 - Attack strategies
 - Time required for runway repair
 - Missile defense
- Model Demonstration

Problem Description

OSD/PA&E

Determine the effectiveness of a missile strike against a runway with each missile containing multiple penetrator sub-munitions.

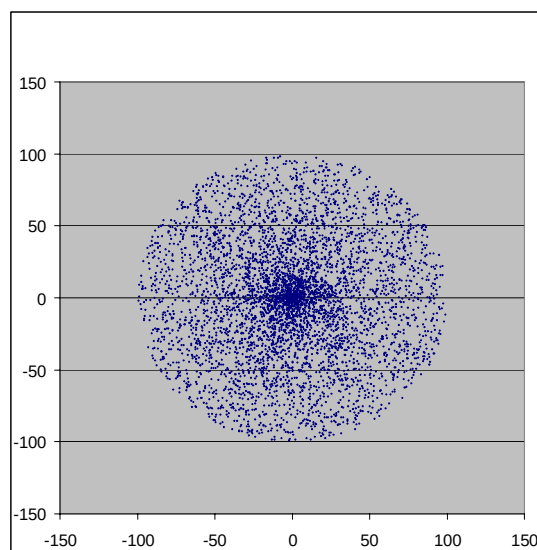
- Airfield is defined by:
 - Length and width of runways/taxiways
 - Length and width of minimum operating strip (MOS)
- Missile strike is defined by:
 - Missile CEP
 - Total number of sub-munitions (sub-munitions per missile time number of missiles)
 - Sub-munition crater diameter
 - Sub-munition distribution pattern

Sub-munition Distribution Methods

Uniform sub-munition / penetrator PATTERNS can be modeled in two ways:

Uniform **Radial** Distribution

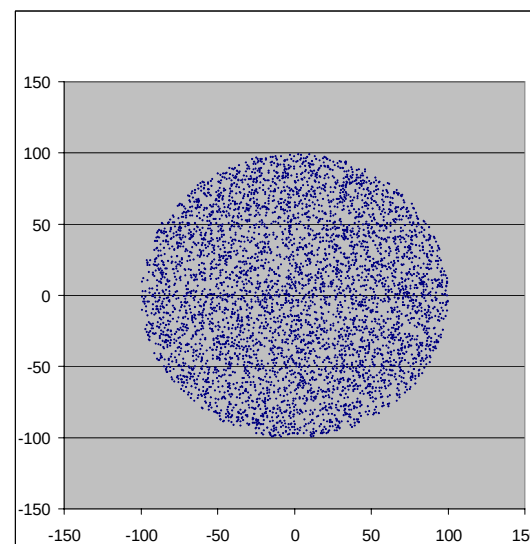
- Random radius less than pattern radius and random angle
- Produces concentration of points near center



Uniform **Radial** Distribution of 5000 points

Circular **Uniform** Distribution

- Random X and Y coordinates
- Eliminate points outside pattern radius
- Uniform density of points



Circular **Uniform** Distribution of 5000 points

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Runway Closing Heuristics

Statistical Analysis

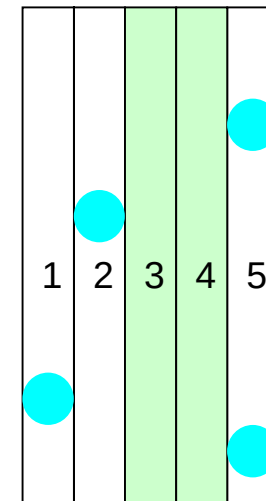
OSD/PA&E

- Divide the runway into **T** sections, each with a width equal to the crater diameter.
- Define **L** as the number of contiguous sections required to meet the minimum width requirements.
- Define **N** as the total number of penetrators.

Problem becomes:

Determine the probability that a missile strike with N penetrators will leave at least L contiguous sections of runway clear.

Runway Width



$$T = \frac{\text{runway width}}{\text{crater diameter}} = 5$$

$$L = \frac{\text{minimum required width}}{\text{crater diameter}} = 2$$

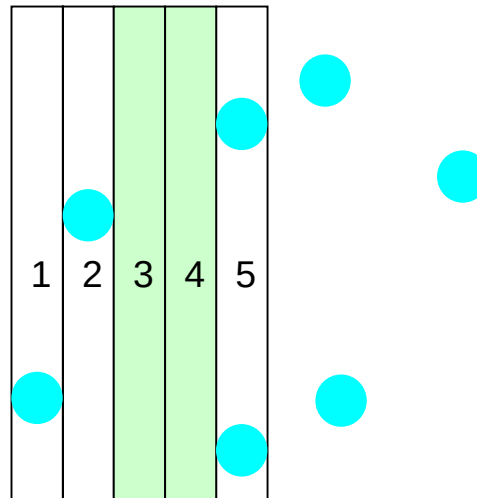
$$N = 7$$

Runway Closing Heuristics

Statistical Analysis

Break the problem into three parts:

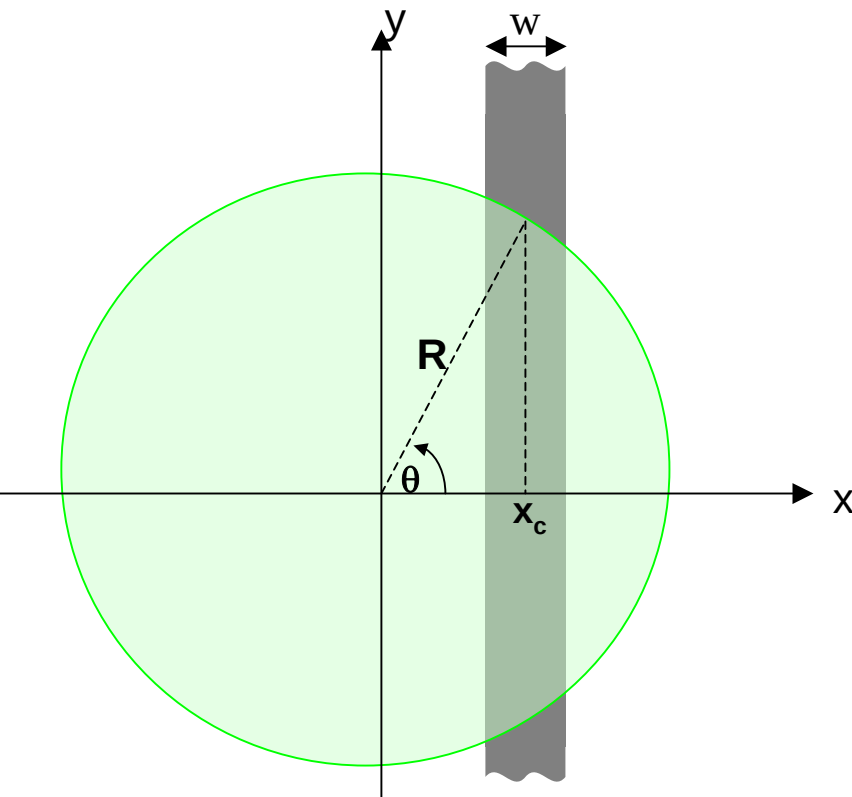
1. Determine the probability that m penetrators will hit the runway, where $0 \leq m \leq N$
2. Determine the probability that if m penetrators hit the runway at least one penetrator will hit exactly S of the T sections, where $0 \leq S \leq T$.
3. Determine the probability that if S of T sections are hit there will be L contiguous open sections.



Runway Closing Heuristics

1. Sub-munitions On Target

OSD/PA&E



w = runway width

R = radius of weapon pattern

x_c = x-coord of runway center (miss distance)

Let $\mathbf{P}_x$ be the fraction of penetrators that hit the runway for a given miss distance $\mathbf{X}_c$

$$\mathbf{P}_x = \frac{\text{Area of Affected Runway}}{\text{Area of Weapon Pattern}}$$

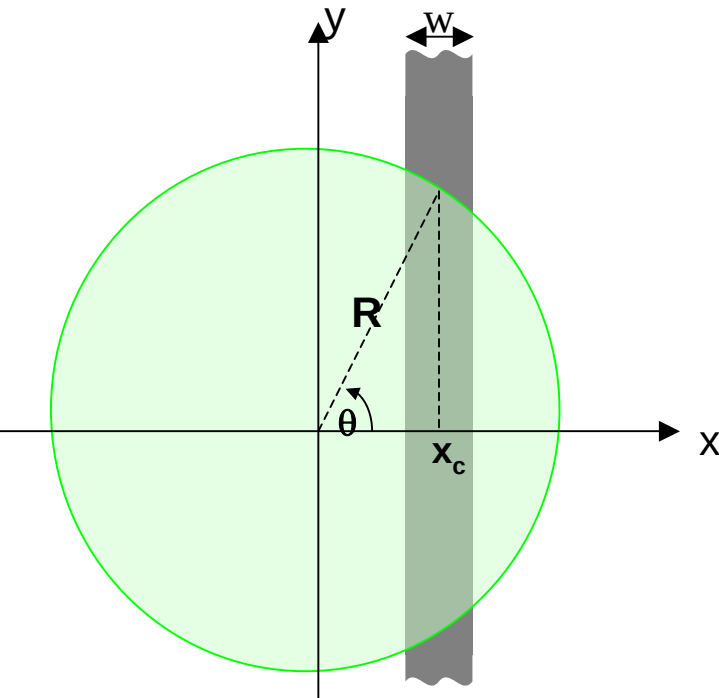
$$\approx \frac{2wR\sin\theta}{\pi R^2} = \frac{2w\sqrt{R^2 - x_c^2}}{\pi R^2}$$

This approximation requires $R > w$ and a circular uniform distribution

Runway Closing Heuristics

1. Sub-munitions On Target

OSD/PA&E



The probability that a given penetrator will hit the runway, P_A , is found by multiplying the probability P_x by the probability that the miss distance will be X_c (normal distribution along X based on the CEP) and integrating over all X

$$P_A = \frac{2w}{\pi \cdot R^2 \sigma \cdot \sqrt{2\pi}} \int_{-R}^R \sqrt{R^2 - x^2} e^{-R^2/4\sigma^2} dx \quad \text{where} \quad \sigma = \frac{CEP}{\sqrt{2 \ln 2}}$$

$$P_A = \frac{w}{\sigma \cdot \sqrt{2\pi}} e^{-R^2/4\sigma^2} [Bessell(0, R^2 / 4\sigma^2) + Bessell(1, R^2 / 4\sigma^2)]$$

If There are N total penetrators, the probability that m of them will strike the runway is given by the m^{th} binomial coefficient of the probability P_A .

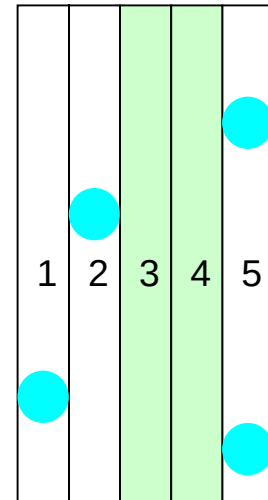
$$P_m(N) = \frac{N!}{m!(N-m)!} P_A^m (1 - P_A)^{(N-m)}$$

Runway Closing Heuristics

2. Sections Hit

OSD/PA&E

Runway Width



$P_S(m, T)$ = The probability that at least one of **m** hits will land in exactly **S** of the **T** sections of the runway, with $0 \leq \mathbf{S} \leq \mathbf{T}$

$$P_S(m, T) = \frac{T!}{S!(T-S)!} \sum_{i=0}^S \frac{(-1)^i S!(S-i)^m}{i!(S-i)! T^m}$$

$$P_S(4, 5) = 0.576 \quad \text{for } S = 3$$

$P_S(N, T)$ = The probability that in an attack of **N** penetrators at least one penetrator will land in exactly **S** of the **T** sections of the runway, with $0 \leq \mathbf{S} \leq \mathbf{T}$

$$P_S(N, T) = \sum_{m=S}^N P_m(N) P_S(m, T)$$

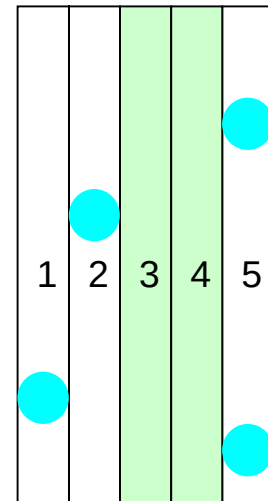
T = rwy selections = width/crater size, 5
S = rwy sections hit, 3
m = number of attempts, 4
L = number of contiguous, unhit sections, 2

Runway Closing Heuristics

3. Contiguous Open Sections

OSD/PA&E

Runway Width



$P_L(T, S) =$ Probability that there are at least **L** contiguous open sections when **S** of **T** sections have been hit

$$P_L(T, S) = \frac{S!(T-S)!}{T!} \sum_{i=1}^{\min\left(\frac{T-S}{L}, S+1\right)} (-1)^{i+1} \frac{(S+1)!}{i!(S+1-i)!} \frac{(T-iL)!}{S!(T-iL-S)!}$$

$$P_L(5, 3) = 0.400 \quad \text{for } L = 2$$

$P_L(m, T) =$ Probability that there are at least **L** contiguous open sections if **m** penetrators hit the runway.

$$P_L(m, T) = \sum_{S=0}^T P_L(T, S) * P_S(m, T)$$

$$P_{L=2}(4, 5) = 0.440$$

T = rwy selections = width/crater size, 5

S = rwy sections hit, 3

m = number of attempts, 4

L = number of contiguous, unhit sections, 2

Runway Closing Heuristics

Cutting the Runway

$P_L(N,T)$ = Probability that **N** penetrators shot at the runway will **NOT** cut the runway.

$$P_L(N,T) = \sum_{S=0}^T P_L(T,S) * P_S(N,T)$$

Probability that **N** penetrators shot **will** cut the runway is just.

$$P_k = 1 - P_L(N,T)$$

Example:

Num penetrators = 70

Runway Width = 150'

Crater diameter = 10'

Min Width = 50'

Missile CEP = 150'

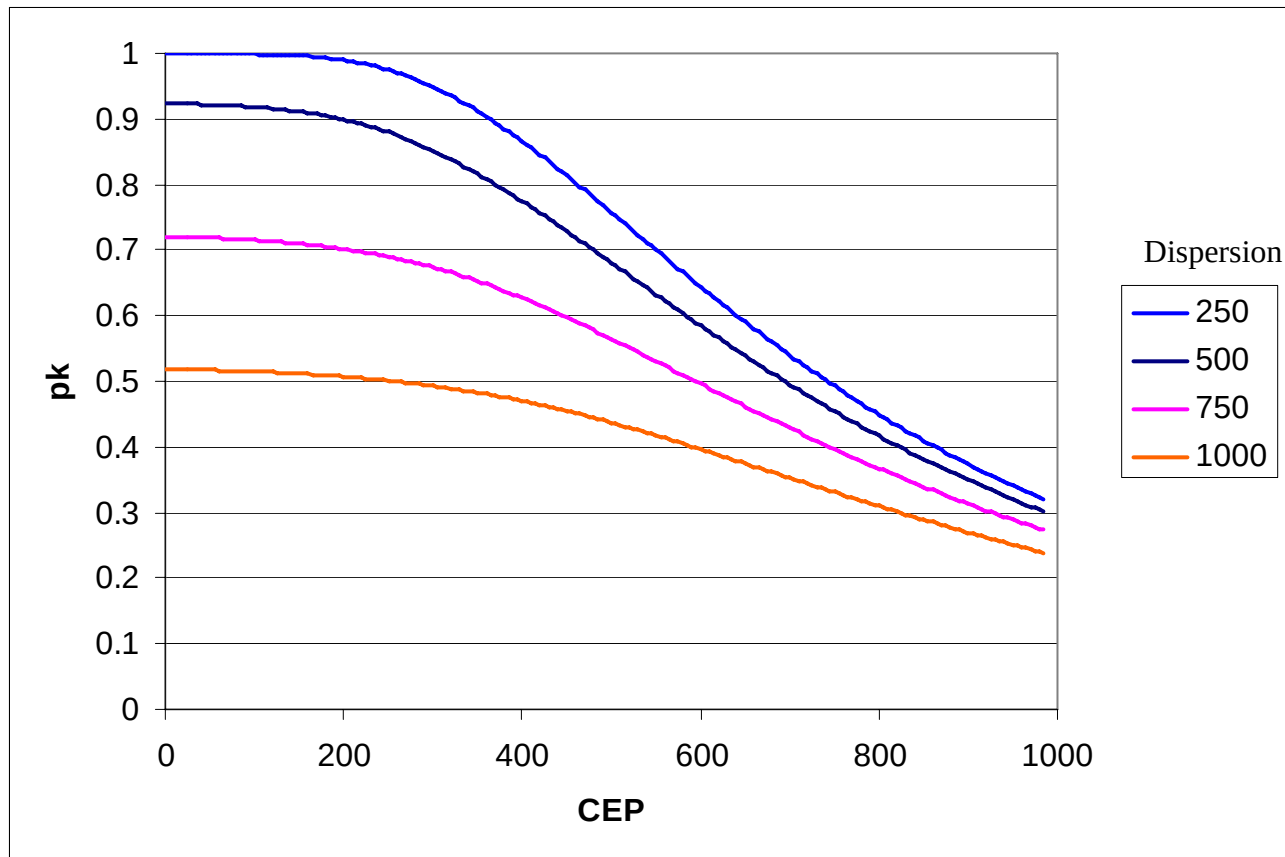
Penetrator dispersion = 1000'

Total penetrators on runway = 7

$P_k = 0.51$

Pk as a function of CEP

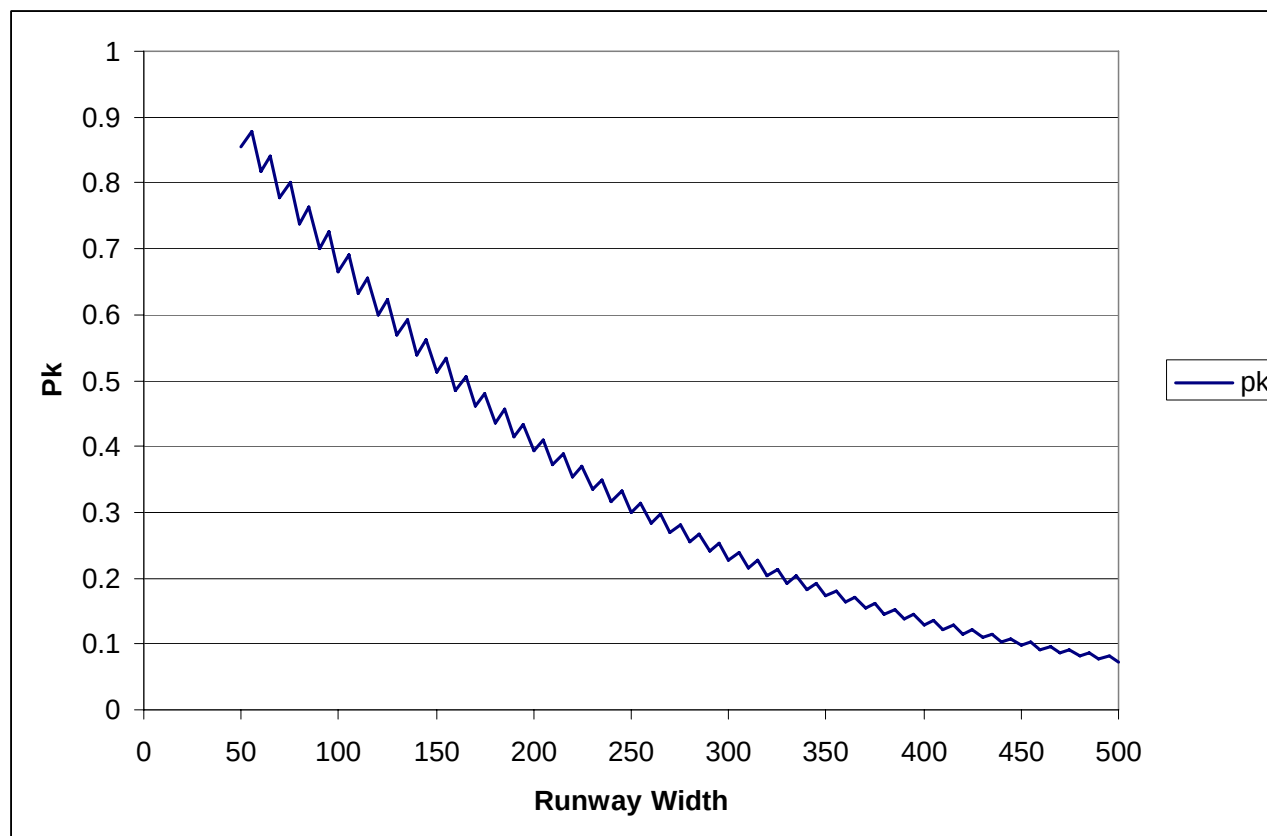
OSD/PA&E



Runway Width = 150
 Minimum Width = 50
 Crater Diameter = 10
 Num Penetrators = 70

Pk as a function of Runway Width

OSD/PA&E



Minimum Width = 50
 Dispersion = 1000
 Crater Diameter = 10
 Num Penetrators = 70
 CEP = 150

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SLICR Model Description

Simulation of Linear Interdiction, Cratering and Repair

OSD/PA&E

- **SLICR is a Monte Carlo simulation of the probability of closing a linear target (runway, taxiway, road, etc.)**
- **Warheads can have unitary or sub-munition (penetrator) payloads**
- **INPUTS (Primary)**
 - Target length and width
 - Additional Targets, e.g., runways as separate targets or as a single target
 - Minimum Operating Segment length and width (MOS) criteria
 - Unitary or sub-munition crater diameter
 - Number of sub-munitions and dispersal radius
 - Missile CEP
 - Weapon and sub-munition reliability
 - Weapon Aimpoint Methodology
- **OUTPUTS**
 - The probability of closing the linear target as a function of the number of warheads
 - Average minimum number of craters that require repair to open a section of target that meets the MOS criteria
 - Estimated time to repair the runway, assuming various criteria
 - Effect of restrikes to reclose the runway and additional repairs needed to reopen

SLICR Model Description

Methodology

- Determine the number of cuts required
- Randomly disperse sub-munitions based on missile CEP, number of sub-munitions and dispersion
- Search the target area to see if there is any area that meets the MOS criteria
- If not, search the target area for the region that requires the fewest repairs to meet the MOS criteria
- Repeat for each Monte Carlo run

SLICR - Inputs

	A	B	C	D	E
1	Airstrips -->	Airstrip 1	Airstrip 2	Airstrip 3	Airstrip 4
2	Airstrip Length	12000			
3	Airstrip Width	200			
4	Airstrip Center X	0			
5	Airstrip Center Y	0			
6	Airstrip Angle (0-360)	0			
7	Min Length	5000			
8	Min Width	50			
9	Delivery Type	Submunitions			
10	Crater Diameter	10.00			
11	# Submunitions	70			
12	CEP	150.00			
13	Dispersion Radius	1000			
14	Distribution Method	Circular			
15	Aimpoint Method	Center of Airfield			
16	Missile Reliability	1.00		New Simulation	
17	Subm. Reliability	1.00		Quit Monte Carlo	
18	Damage Goal (0-1)	0.900		Add Missiles	
19	Number Runs (Monte Carlo)	1000			
20	Min Number Weapons/Cut	1			
21	Max Number Weapons/Cut	10		Distort Map Off	
22	# of Cuts (0 for default)	2		Reset	
23					

SLICR - Inputs

	A	B	C	D	E
1	Airstrips -->	Airstrip 1	Airstrip 2	Airstrip 3	Airstrip 4
2	Airstrip Length	12000			
3	Airstrip Width	200			
4	Airstrip Center X	0			
5	Airstrip Center Y	0			
6	Airstrip Angle (0-360)	0			
7	Min Length	5000			
8	Min Width	50			
9	Delivery Type	Submunitions			
10	Crater Diameter	Submunitions			
11	# Submunitions	Unitary			
12	CEP	Dumb Bombs			
13	Dispersion Radius	Smart Bombs			
14	Distribution Method	Circular			
15	Aimpoint Method	Center of Airfield			
16	Missile Reliability	1.00		New Simulation	
17	Subm. Reliability	1.00		Quit Monte Carlo	
18	Damage Goal (0-1)	0.900		Add Missiles	
19	Number Runs (Monte Carlo)	1000			
20	Min Number Weapons/Cut	1		Distort Map Off	
21	Max Number Weapons/Cut	10		Reset	
22	# of Cuts (0 for default)	2			
23					

SLICR - Inputs

	A	B	C	D	E
1	Airstrips -->	Airstrip 1	Airstrip 2	Airstrip 3	Airstrip 4
2	Airstrip Length	12000			
3	Airstrip Width	200			
4	Airstrip Center X	0			
5	Airstrip Center Y	0			
6	Airstrip Angle (0-360)	0			
7	Min Length	5000			
8	Min Width	50			
9	Delivery Type	Submunitions			
10	Crater Diameter	10.00			
11	# Submunitions	70			
12	CEP	150.00			
13	Dispersion Radius	1000			
14	Distribution Method	Circular			
15	Aimpoint Method	Radial			
16	Missile Reliability	Circular			
17	Subm. Reliability	1.00			
18	Damage Goal (0-1)	0.900			
19	Number Runs (Monte Carlo)	1000			
20	Min Number Weapons/Cut	1			
21	Max Number Weapons/Cut	10			
22	# of Cuts (0 for default)	2			
23					

New Simulation

Quit Monte Carlo

Add Missiles

Distort Map Off

Reset

SLICR - Inputs

	A	B	C	D	E
1	Airstrips -->	Airstrip 1	Airstrip 2	Airstrip 3	Airstrip 4
2	Airstrip Length	12000			
3	Airstrip Width	200			
4	Airstrip Center X	0			
5	Airstrip Center Y	0			
6	Airstrip Angle (0-360)	0			
7	Min Length	5000			
8	Min Width	50			
9	Delivery Type	Submunitions			
10	Crater Diameter	10.00			
11	# Submunitions	70			
12	CEP	150.00			
13	Dispersion Radius	1000			
14	Distribution Method	Circular			
15	Aimpoint Method	Center of Airfield			
16	Missile Reliability	Center of Airfield			
17	Subm. Reliability	Center of Left-most Airstrip			
18	Damage Goal (0-1)	Center of Right-most Airstrip			
19	Number Runs (Monte Carlo)	Center of Each Airstrip			
20	Min Number Weapons/Cut	Multiple Aimpoints			
21	Max Number Weapons/Cut	10			
22	# of Cuts (0 for default)	2			
23					

Simulation

Monte Carlo

Missiles

Distort Map Off

Reset

SLICR Model Example

Airstrips -->

Airstrip 1

Airstrip 2

Airstrip 3

Airstrip 4

Airstrip 5

Airstrip 6

Airstrip 7

Airstrip 8

Airstrip 9

Airstrip 10

Airstrip Length

12000

Airstrip Width

150

Airstrip Center X

0

Airstrip Center Y

0

Airstrip Angle (0-360)

0

Min Length

5000

Min Width

50

Delivery Type

Submunitions

Crater Diameter

10.00

Submunitions

70

CEP

150.00

Dispersion Radius

1000

Distribution Method

Circular

Aimpoint Method

Center of Airfield

Missile Reliability

1.00

Subm. Reliability

1.00

Damage Goal (0-1)

0.900

Number Runs (Monte Carlo)

1000

Min Number Weapons/Cut

1

Max Number Weapons/Cut

10

of Cuts (0 for default)

2

New Simulation

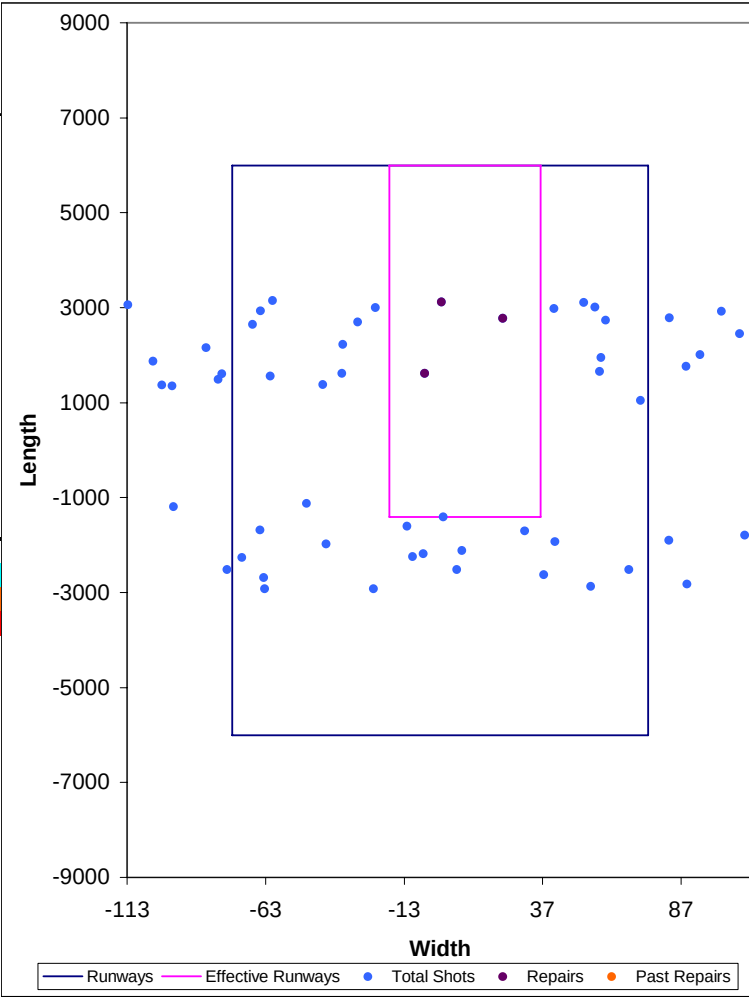
Quit Monte Carlo

Add Missiles

Distort Map Off

Reset

Weapons per Cut	Pk	Ave. Repairs	Std. Dev. # R	Ave. Subm. on T.	Std. Subm. on Tgt
1	0.37	0.4	0.64	14.17	3.60
2	0.90	2.0	1.14	28.07	4.91
3	0.99	3.8	1.41	42.53	6.17



SLICR Model Example

Airstrips -->

Airstrip 1

Airstrip 2

Airstrip 3

Airstrip 4

Airstrip 5

Airstrip 6

Airstrip 7

Airstrip 8

Airstrip 9

Airstrip 10

Airstrip Length

12000

Airstrip Width

150

Airstrip Center X

0

Airstrip Center Y

0

Airstrip Angle (0-360)

0

Min Length

5000

Min Width

50

Delivery Type

Submunitions

Crater Diameter

10.00

Submunitions

70

CEP

150.00

Dispersion Radius

1000

Distribution Method

Circular

Aimpoint Method

Center of Airfield

Missile Reliability

1.00

Subm. Reliability

1.00

Damage Goal (0-1)

0.900

Number Runs (Monte Carlo)

1000

Min Number Weapons/Cut

1

Max Number Weapons/Cut

10

of Cuts (0 for default)

2

New Simulation

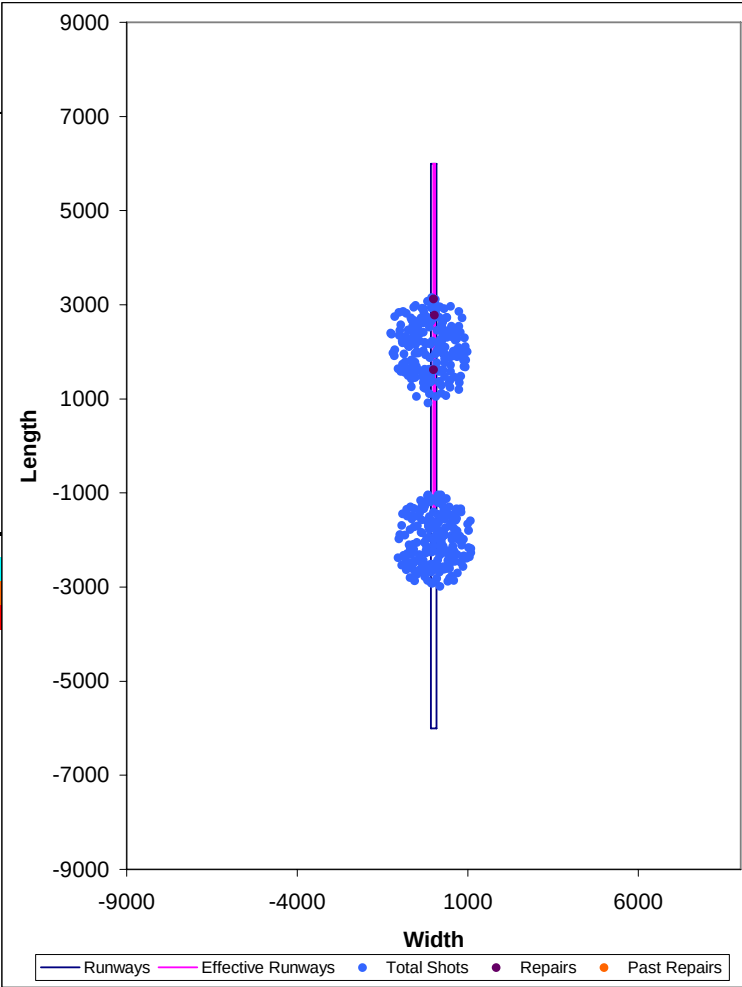
Quit Monte Carlo

Add Missiles

Distort Map On

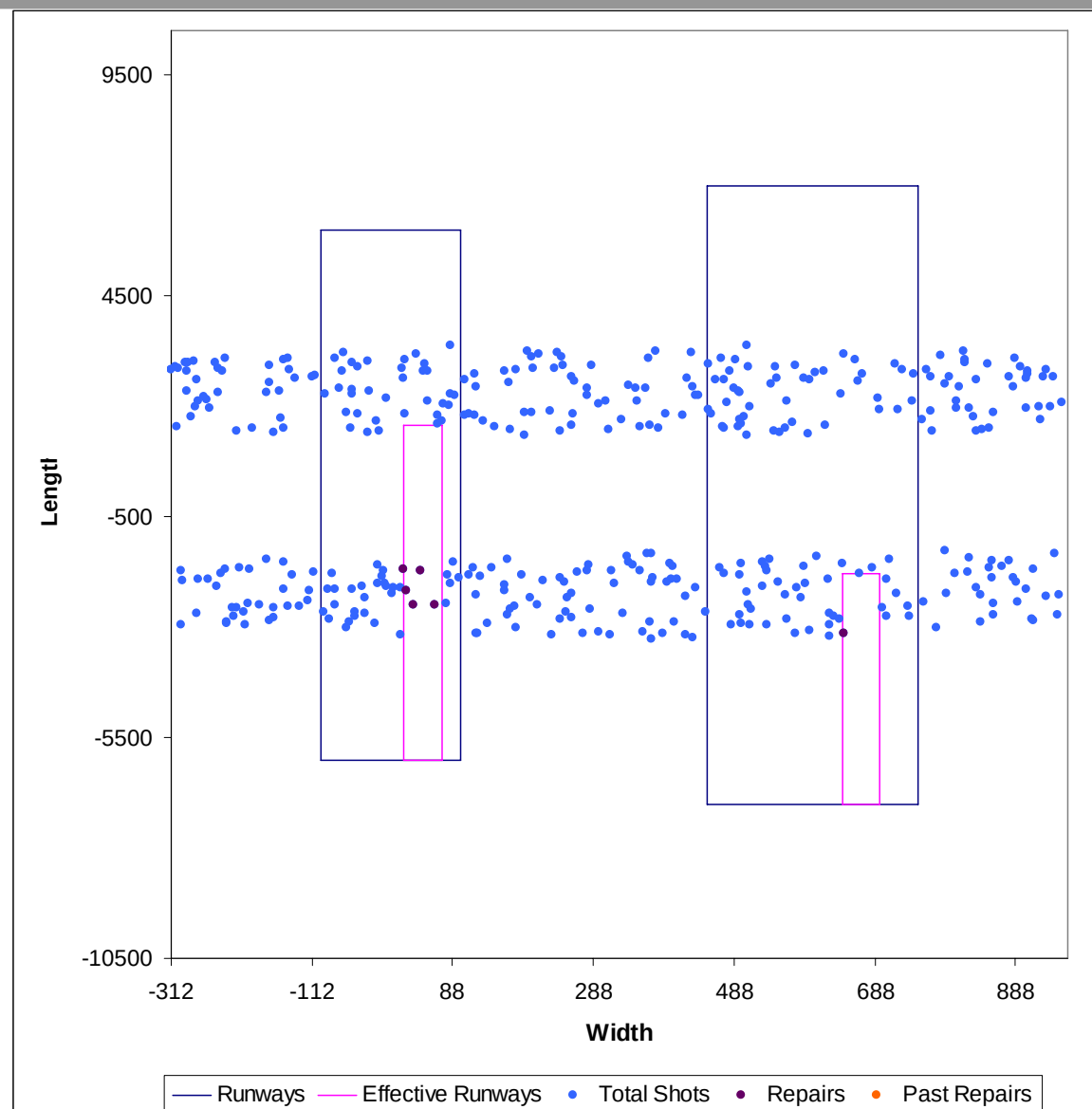
Reset

Weapons per Cut	Pk	Ave. Repairs	Std. Dev. # R	Ave. Subm. on T.	Std. Subm. on Tgt
1	0.37	0.4	0.64	14.17	3.60
2	0.90	2.0	1.14	28.07	4.91
3	0.99	3.8	1.41	42.53	6.17



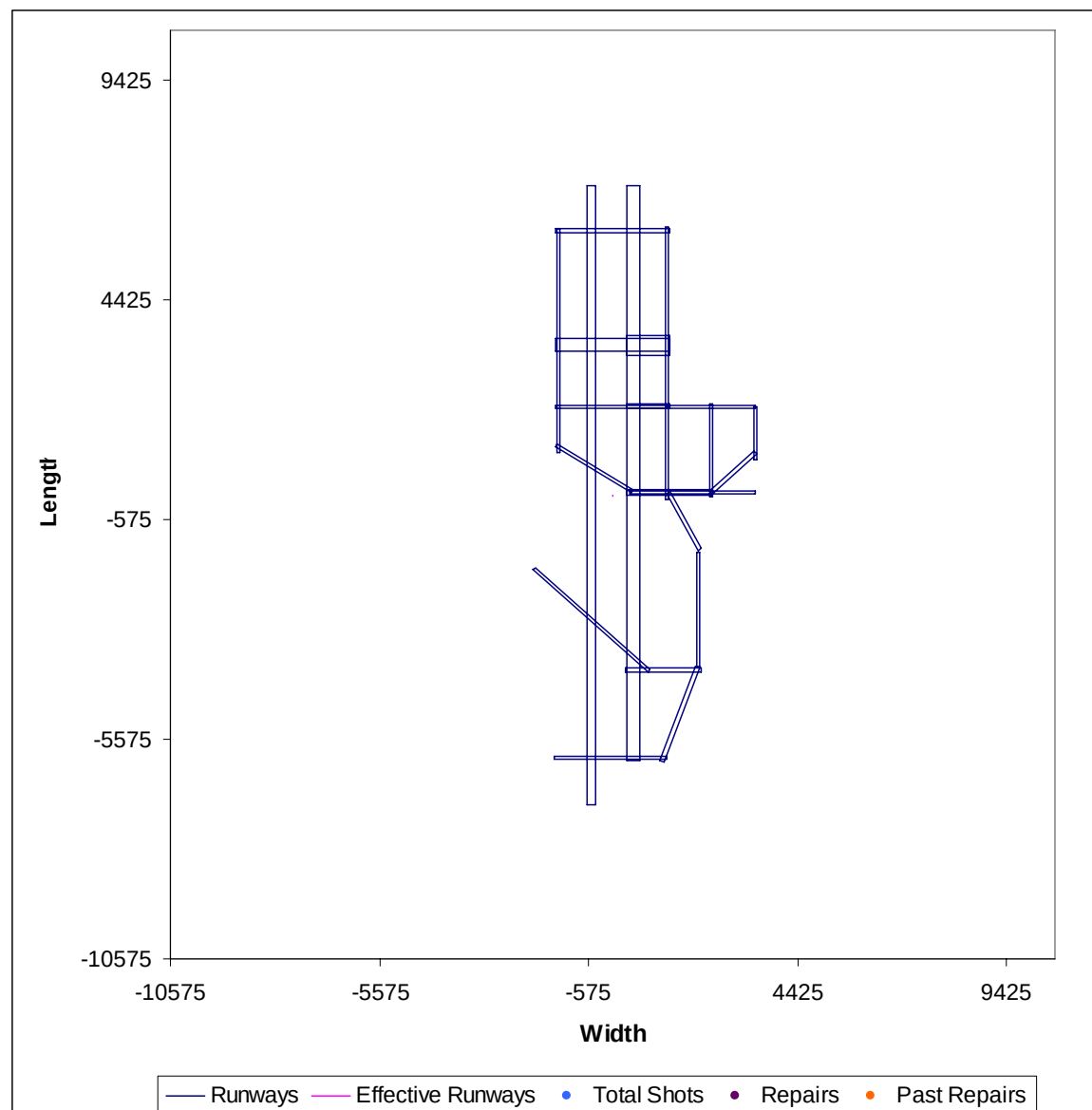
SLICR Model Example – Parallel Runways

OSD/PA&E



SLICR Model Example – Complex Airfield

OSD/PA&E



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SLICR Model Description

Repair Methodology

- Three methods for calculating repair time
 - Repair minimum number of craters
 - Repair average number of craters
 - Repair accessible strip
- Repair times based on Air Force engineering runway repair data for craters less than 20 ft.
 - Crater evaluation – 3min per crater
 - MOS selection – 30 min
 - Unexploded ordinance/FOD removal – 60 min
 - Crater repair – 65 min first crater, 35 min each additional crater

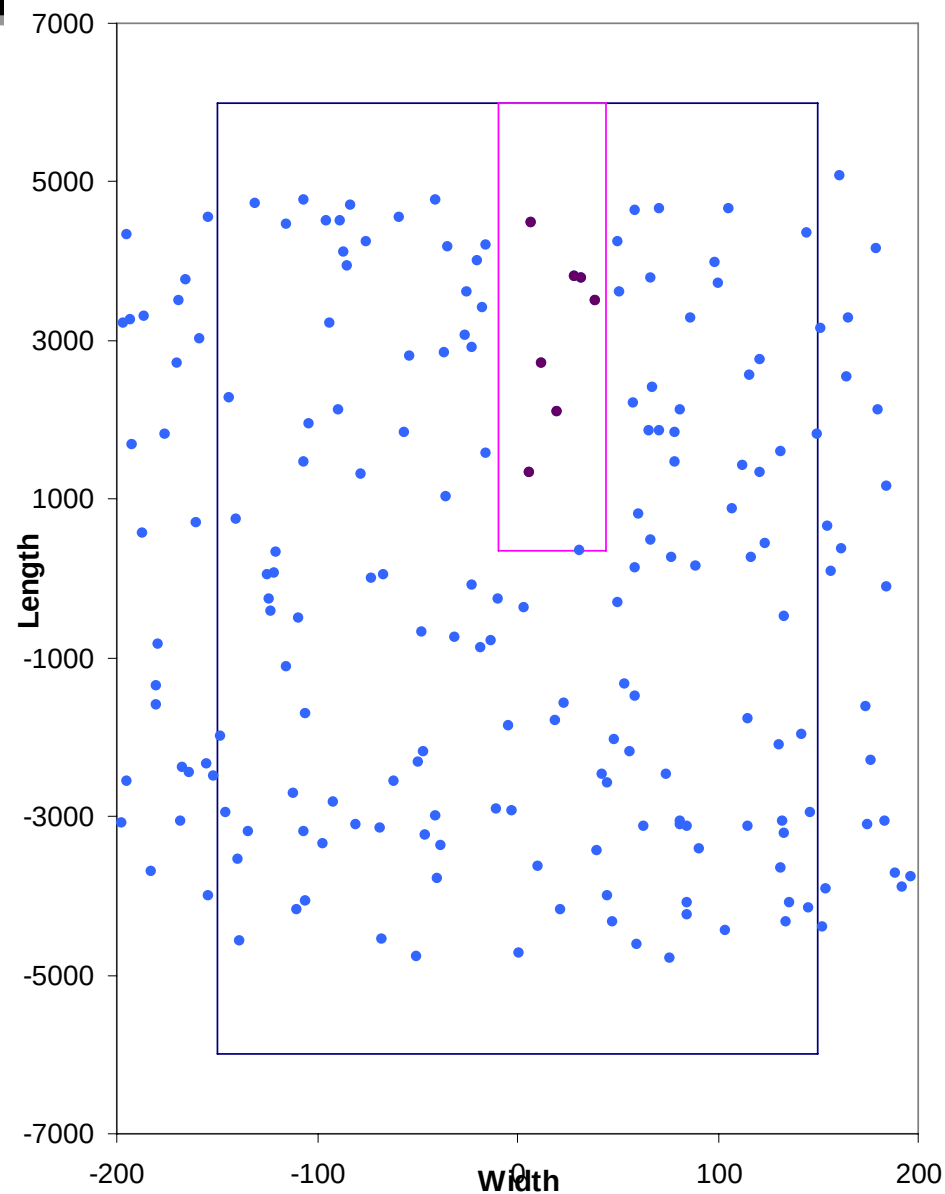
Repair Time – Minimum Repairs

Evaluate all craters

Select the **fewest craters** to repair a section meeting the MOS criteria

Clear unexploded ordnances

Repair craters



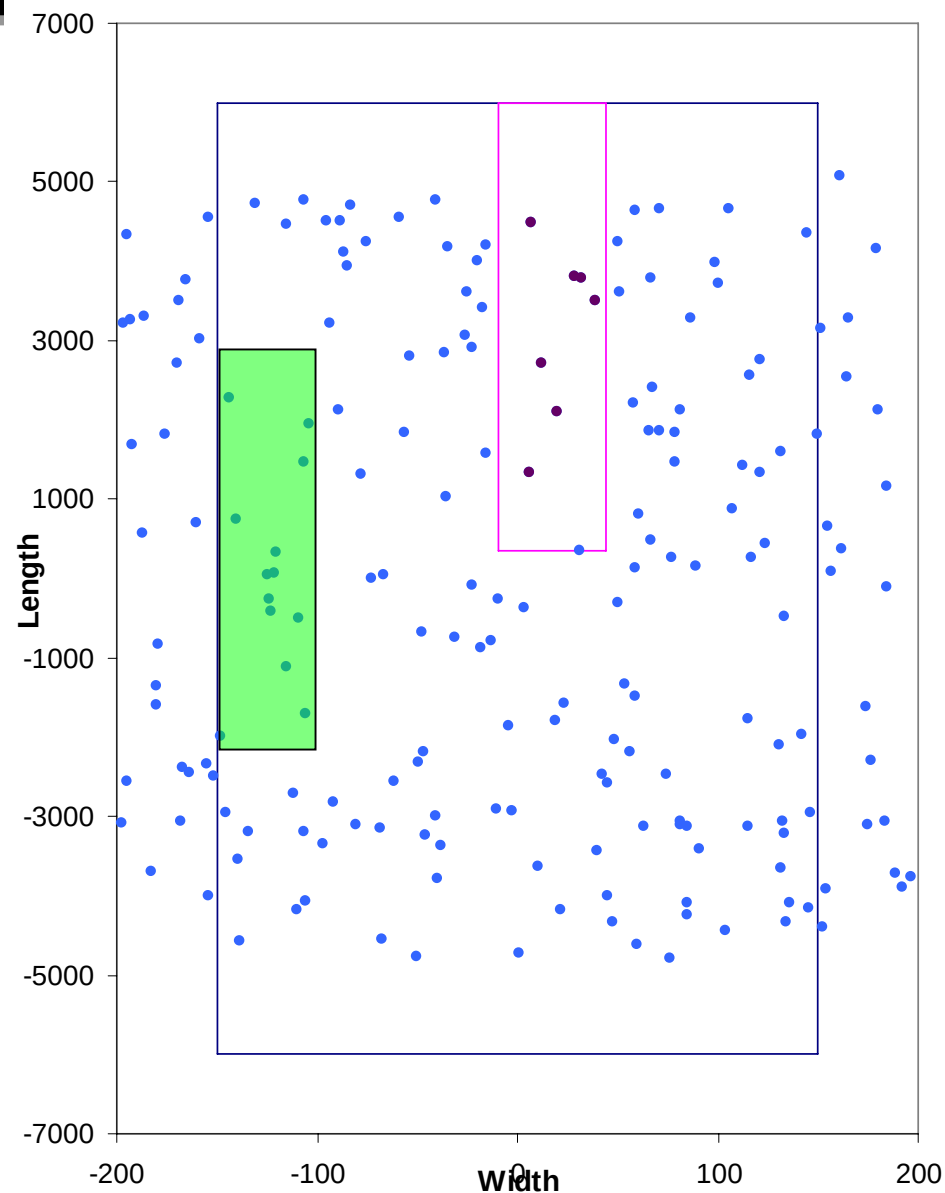
Repair Time – Average Time

Evaluate only the craters in an **average region** that meets the MOS criteria

Clear unexploded ordnances

Repair the average number of the craters for the given MOS area

NOTE: the number of craters to repair is defined as the density of craters on the runway multiplied by the MOS area



Repair Time – Most Accessible

Evaluate all craters in a region six times the MOS criteria.

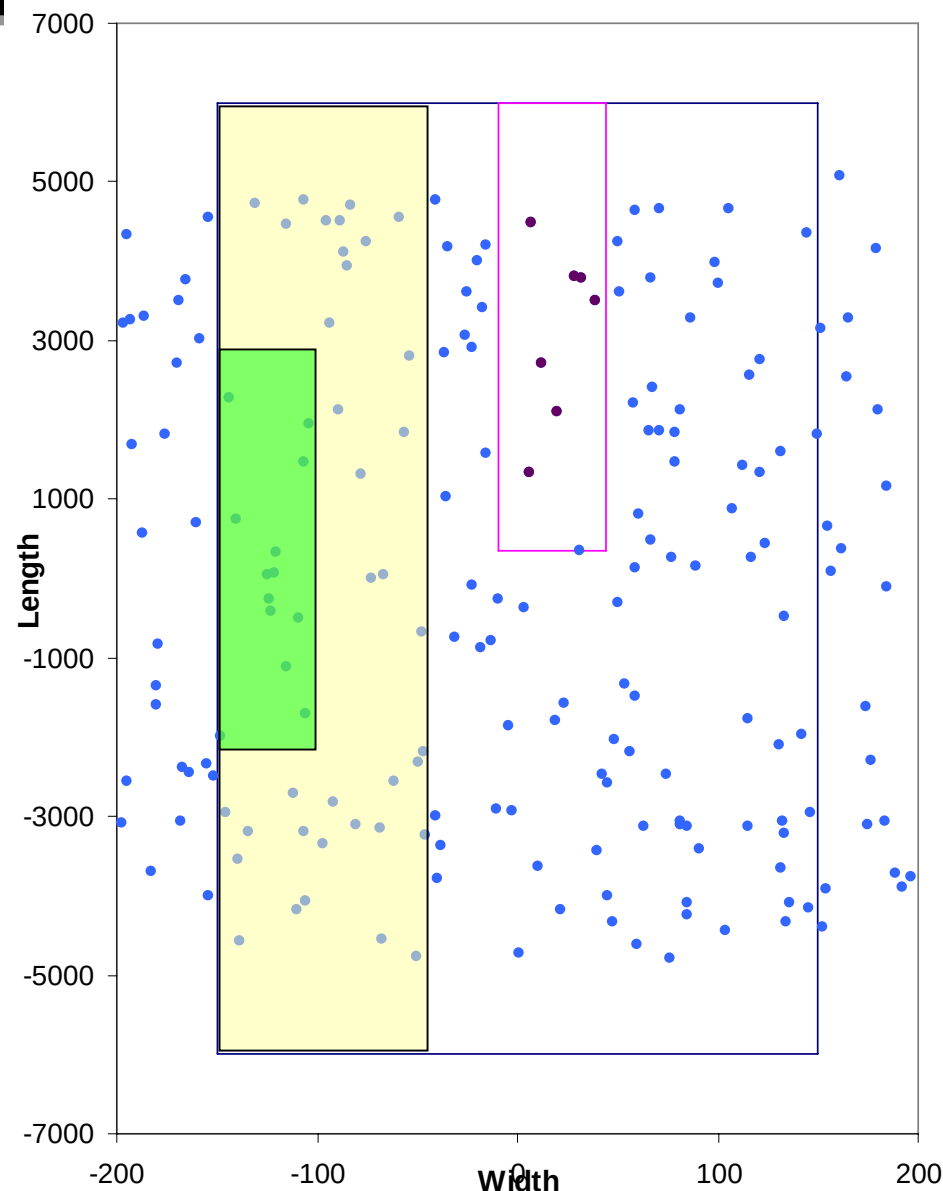
NOTE: Usually this will be a region of the runway that is most accessible by crew and aircraft.

Repair the average number of the craters for the given MOS area

Clear unexploded ordnances

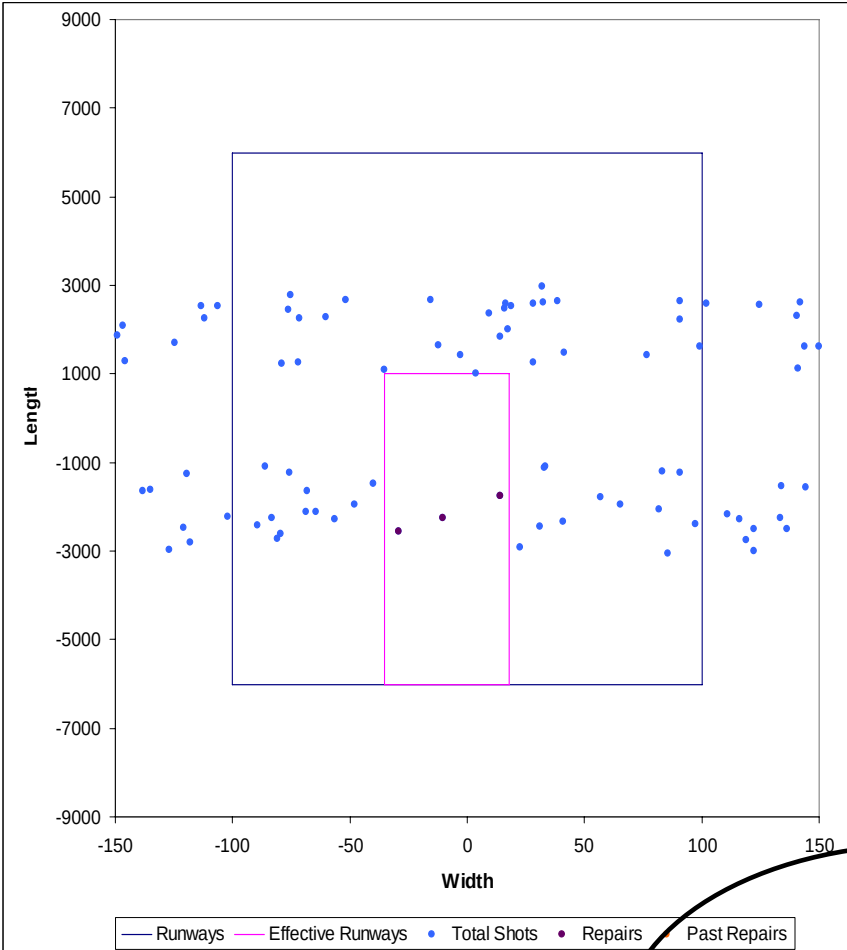
Repair craters

NOTE: the number of craters to repair is defined as the density of craters on the runway multiplied by the MOS area.



Repair Time – Outputs

OSD/PA&E



Weapons per Cut	Pk	Ave. Repairs	Std. Dev. # R	Ave. Subm. on T.	Std. Subm. on Tgt	Min Repair Time	Ave Repair Time	Acc Repair Time
1	0.24	0.3	0.46	18.47	3.89	212	196	220
2	0.85	1.6	1.01	37.12	5.43	304	272	317
3	0.98	3.2	1.31	55.35	6.70	428	348	414

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Missile Defense

Model missile defense by degrading the threat missile reliability. The effective reliability (R_{eff}) can be calculated by

$$R_{\text{eff}} = R \frac{\frac{m}{n} (1 - P)^n + \left(s - \frac{m}{n} \right)}{s}$$

R_{eff} = Effective threat missile reliability
 R = Native threat missile reliability
 P = Interceptor effectiveness
 m = Number of interceptors used
 n = Number of interceptors per threat missile
 S = Number of threat missiles

SLICR Model Point of Contact

OSD/PA&E

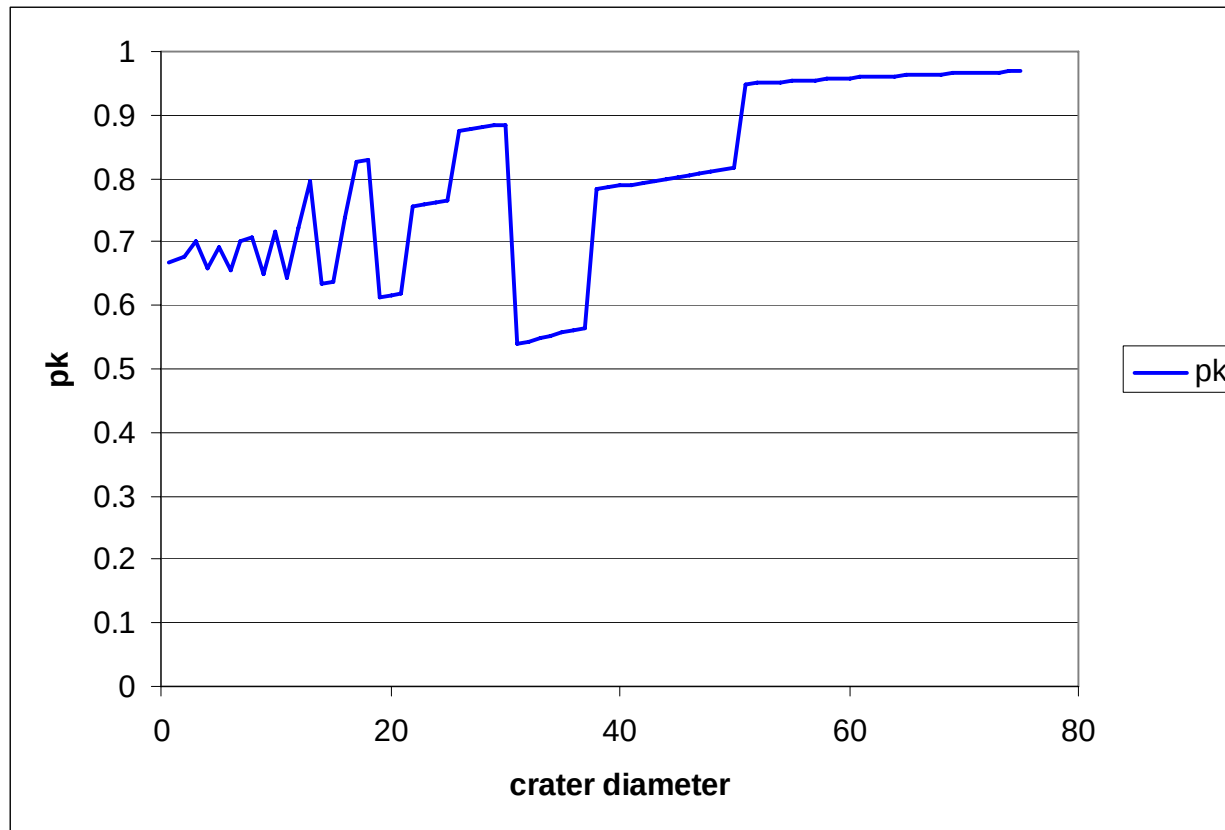
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Model Demonstration

BACKUP SLIDES

Pk as a function of crater diameter

OSD/PA&E



Runway Width = 150
Minimum Width = 50
Dispersion = 1000
Num Penetrators = 70
CEP = 150